Journal of the Institute of Petroleum

VOL. 40 OCTOBER 1954 No. 370

CONTENTS

SYMPOSIUM ON METAL-WORKING OILS
PART II. METAL-FORMING

The Role of Friction in Metal-working Processes
By Hugh Ford

Some Observations on Conditions of Lubrication in Wire-drawing Dies
By D. G. Christopherson, O.B.E., H. Naylor, and J. Wells

Some Lubrication Effects in Deep Drawing Operations
By E. M. Loxley and P. Freeman

Study of Lubrication in Wire Drawing by an Electrical Method
By A. E. Ranger and J. G. Wistreich

Lubrication of Strip in Cold Rolling Mills
By R. B. Sims

Lubricants for Tube and Bar Drawing
By A. L. H. Perry (Associate Fellow)

Tube-drawing Oils: The Function of Fatty and E.P. Additives
By J. S. McFarlane and A. J. Wilson

Metal-working Lubrication in the Bolt Industry
By G. H. Townend

Discussion

Abstracts 1538–1731

Book Reviews

Additions to Library

PRICE 10s 0D A COPY OR
£4-14-6 YEARLY *POST FREE*

Published by the Institute of Petroleum 26 Portland Place London W1

Printed in Great Britain by Richard Clay and Company Ltd Bungay Suffolk

COUNCIL, 1954–55

President

Lt.-Col. S. J. M. Auld, O.B.E., M.C., D.Sc.

Past-Presidents

Sir Andrew Agnew, C.B.E.
T. Dewhurst, A.R.C.S.
A. E. Dunstan, D.Sc., F.R.I.C.
E. A. Evans, M.I.Mech.E., F.R.I.C.
F. H. Garner, O.B.E., Ph.D., F.R.I.C.
H. S. Gibson, C.B.E., M.A., M.I.Mech.E.
C. A. P. Southwell, C.B.E., M.C., B.Sc.

Vice-Presidents

H. Hyams
F. Morton, Ph.D., D.Sc., F.R.I.C.
J. A. Oriel, C.B.E., M.C., M.A., B.Sc., F.R.I.C., M.I.Chem.E.
H. E. F. Pracy, B.A., M.I.Chem.E.
R. B. Southall, C.B.E.
G. H. Thornley, M.Sc.

Members of Council

W. S. Ault, B.A.
V. Binke, B.Sc., LL.M., F.R.I.C.
C. D. Brewer, M.I.Mech.E.
E. J. Dunstan, M.Sc., M.I.Chem.E.
E. B. Evans, M.Sc., Ph.D., F.R.I.C.
F. L. Garton, M.A., B.Sc.
A. J. Goodfellow, B.Sc., A.R.I.C.
A. C. Hartley, C.B.E., F.C.G.I., B.Sc.(Eng.), M.I.C.E., M.I.Mech.E.
E. LeQ. Herbert, B.Sc., F.R.I.C., M.I.Chem.E.
E. C. Masterson, B.Sc.
J. S. Parker, M.A., B.Sc.
A. J. Ruthven-Murray, C.M.G., M.A., B.Sc.
D. L. Samuel, B.Sc., A.R.I.C.
G. H. Smith, Ph.D.
A. R. Stark, B.Sc., A.R.I.C.
E. J. Sturgess, B.Sc.
W. H. Thomas, A.R.S.M., F.R.I.C.
O. F. Thompson, O.B.E.
A. T. Wilford, B.Sc., F.R.I.C.
C. G. Williams, D.Sc., M.I.Mech.E., F.R.Ae.S.
C. S. Windebank, B.Sc., M.S.

Ex-Officio

S. A. Berridge, Fawley Branch
W. H. Davies, London Branch
H. H. Ballard, Northern Branch
W. M. Stirling, A.H-W.C., A.M.I.E.E., Scottish Branch
N. W. Grey, M.I.Chem.E., South-Eastern Branch
J. A. Green, South Wales Branch

Honorary Secretary

C. Chilvers, B.Sc., F.R.I.C.

Honorary Treasurer

G. H. Coxon

General Secretary

D. A. Hough, T.D., F.I.A.C.

Honorary Editor

E. B. Evans, M.Sc., Ph.D., F.R.I.C.

Honorary Associate Editor

D. L. Samuel, B.Sc., A.R.I.C.

Editor

George Sell

Honorary Secretaries of Branches

Fawley Branch: S. A. Berridge, c/o Esso Petroleum Co. Ltd., Fawley, Southampton.

London Branch: R. F. Leach, M.A., c/o Shell-Mex and B.P. Ltd., Shell-Mex House, Strand, London, W.C.2.

Northern Branch: G. M. Davies, c/o Esso Petroleum Co. Ltd., Mode Wheel Installation, Trafford Wharf Road, Manchester 17.

Persian Gulf Branch: E. J. Sole, c/o Kuwait Oil Co. Ltd., Kuwait, Persian Gulf.

Scottish Branch: W. M. Stirling, A.H-W.C., A.M.I.E.E., Scottish Oils Ltd., Middleton Hall, Uphall, Broxburn, W. Lothian.

South-Eastern Branch: J. R. Moore, Fisher Governor Co. Ltd., Airport Works, Rochester, Kent.

South Wales Branch: D. J. Lewis, National Oil Refineries Ltd., Llandarcy, Glam.

Stanlow Branch: A. S. Brooman, B.Sc., 11 Grange Crescent, Hooton, Wirral, Cheshire.

Trinidad Branch: E. G. Everett, c/o United British Oilfields of Trinidad Ltd., Point Fortin, Trinidad, B.W.I.

VOL. 40 NO. 370 OCTOBER 1954

SYMPOSIUM ON METAL-WORKING OILS
PART II. METAL-FORMING

THE ROLE OF FRICTION IN METAL-WORKING PROCESSES

By HUGH FORD*

SYNOPSIS

The paper examines present knowledge on the coefficient of friction in metal-working processes and compares typical values with those found in the usual slider tests.

Recent experimental determinations of the coefficient for lubricated conditions in plane compression and cold rolling tests are described, and the possible mechanism of friction is suggested.

INTRODUCTION

WHEN a metal is undergoing plastic deformation by the action of external forces on a contacting (non-plastic) platen or die, relative motion must normally occur between the plastic and non-plastic contacting surfaces. Such motion takes place under high stresses, and an exceptional lubrication problem arises. The question as to the nature of the friction or interaction of the surfaces is clearly of great interest and importance, because the amount of the friction may be such that the deformation process cannot be carried out, or at least the metal is so seriously damaged that it is no longer satisfactory for its purpose.

It is unnecessary to describe in detail the fundamental notions of boundary friction in view of the recent discussions on this subject.[1, 2] A few basic facts and ideas must, however, be summarized in so far as they have a bearing on the friction mechanism in metal-working processes.

It may be supposed that the mechanism is essentially that put forward by Bowden [3] and his collaborators and others: that is, that the asperities on the die and the deforming metal interact, with heavy local deformation so that momentary welding occurs and the making and shearing of these very small junctions with the relative movement at the interface gives rise to the frictional force. Even up to very high pressures, it has been shown that such friction is proportional to the applied pressure, and it would therefore seem reasonable to conclude that the coefficient of friction in cold-working processes would be in the range found in the usual dynamic tests. Table I, however, shows typical results from a number of sources for surfaces covered with good lubricants.

These values suggest that friction is generally lower than that in the slider tests, since Bowden and others quote their lowest figures for solid lubricants, in which some chemical action occurs to form an attached surface film. The high pressures in metal-forming processes would suggest that since the height of the asperities must follow something approaching a Gaussian frequency distribution, the number of possible junctions should increase more than linearly and that there might be some interlocking of the asperities in addition and a ploughing action might be expected.

The metal surfaces used in such processes will inevitably be covered with layers of oxide, adhering films of contaminants, and gases, and these have a modifying action on the friction, lowering it considerably compared with clean metals *in vacuo*. Table I was drawn up for contaminated surfaces with lubricant films, but a difference at once appears between the usual slider tests and metal-forming processes: in the latter plastic deformation of the metal is occurring continuously and new surface is being produced, the oxide layer is broken up and the underlying metal is brought into contact with the roll surface. The nature of the die (non-plastic) surface or of any lubricant present must clearly be of major importance in such processes, but a comparison of slider tests with deformation tests shows again that the coefficient is smaller in the latter.

When the rubbing speed is high, much heat is

* Professor of Applied Mechanics, Imperial College, University of London.

developed at the junctions between the asperities, so that they are melted or softened locally and smeared over the surface (Beilby layer). This action should be particularly marked when one of the metals has a lower melting point than the other. If such an action

TABLE I

Source	Type of test	Condition	Coefficient of friction
Bowden [3]	Sliders	Solid and liquid lubricants—wide range	About 0·08 upwards
Forrester [4]	Spherical sliders	Solid and liquid lubricants	0·09 to 0·2
McLellan [5]	Wire drawing	Various experiments	0·05 to 0·12
Ford and Ellis [6]	Cold rolling	Steel and copper strip on steel rolls, normal lubricants	0·04 to 0·08
Baron and Thompson [7]	Wire drawing	Lubricated with soaps, derived coefficient	0·03 to 0·09
Watts and Ford [8]	Plane compression and "cigar" test	Polished surface, graphite lubricant, incremental loading	0·015 to 0·02
Hill [9]	Plane compression and "cigar" test	—	0·015 to 0·05

can occur in metal-forming processes, it suggests that the surface finish with a metal, such as copper, should develop a different kind of surface layer, *e.g.* in cold rolling, than steel, since both metals are rolled with steel rolls.

The general picture presented by the classical slider tests is then that the surface asperities must be prevented from welding together, by interposing a lubricant layer which will be maintained even at the highest pressures.

These considerations must therefore be looked at in the light of tests made in metal-forming researches.

FRICTION IN METAL FORMING

Plane Compression Tests

Fig 1 shows a simple test apparatus [8] in which a flat plate of material (strip) is compressed between flat smooth dies. The material on each side of the die prevents lateral spread of the plate and ensures that the relative movement between the die and material surface increases uniformly from zero at the centre to a maximum at the outside, proportionally with the vertical compression between the dies.

The amount of deformation and the stress distribution in such a test can be exactly specified, and the results can be correlated with the simple tensile yield stress curve. The loading is done incrementally.[8] The technique is to lubricate the surfaces with a solid lubricant, *e.g.* graphite, oleic or stearic acid, apply enough load to cause a small deformation (1 to 2 per cent compression), remove from the dies, relubricate, and so on, in the same impression until the required total compression has been reached. The same apparatus was also used to compress rectangles of the material, sufficiently narrow that the dies completely overlapped the test piece, which accordingly extends both in the lateral and longitudinal directions. The final cigar-like cross-section has been shown by Hill [9] to depend upon the coefficient of friction, which can then be determined. Results by incremental and continuous deformation methods indicate that the coefficient of friction increases to some extent with the amount of relative

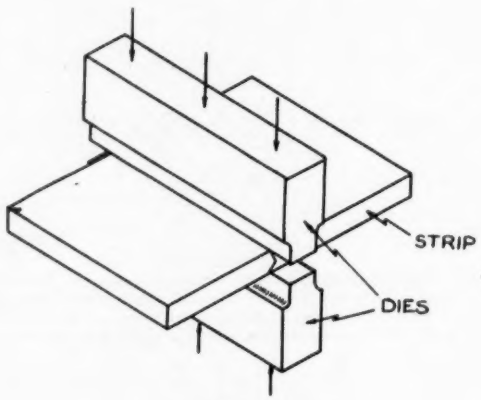


FIG 1

THE PLANE COMPRESSION TEST

motion, as originally suggested by Orowan.[10] For typical "good" lubricants, the coefficient of friction is found to range from 0·015 to 0·05.

Cold Rolling Tests

If the yield stress characteristic of the rolled material is known, then the coefficient of friction and the geometry of the pass are the only quantities which need to be "fed" into the theory, to calculate the roll force and torque in the pass. Alternatively, by measuring the roll force and torque, the coefficient of friction can be chosen to make the theoretical calculation of these quantities fit the measured values. This method has been frequently used, but the coefficient so found depends upon the theory and the yield stress characteristic very sensitively because, the coefficient being small, the contribution it makes to the total roll force ("friction hill") is also small.[6]

A new method of measuring the friction has been developed * from a suggestion by Bland.[11] If a back tension is applied to the strip entering the mill, such that the rolls are just about to skid on the strip, it can be shown that $\mu = G/PR$, where μ is the coefficient of friction, P is the roll force, R is the radius of roll, and G is the roll torque, and the result is independent of rolling theory, the only assumption being that the coefficient of friction is constant over the arc of

* A full account of this work is now under preparation.

contact in the pass. The values of G and P at the critical point can be measured accurately.

The advantages of this method are that the friction is measured under exactly the conditions of the rolling process, and that when the strip starts to slip, the tension can be relaxed and built up again several times in one length of strip, so that the average of several results can be obtained.

A few typical results are given in Table II.

TABLE II

Laboratory mill, polished rolls 4 inch diameter, speed about 30 ft/min

Pass no.	Lubricant	Coefficient of friction
	(*a*) Mild steel tests—annealed strip—approximately 20 per cent passes	
First	Clean and dry	0·085
,,	Paraffin oil	0·080
,,	68 : 615 graphite in oil	0·072
,,	Vacuum rolling oil 546	0·070
,,	,, ,, ,, 40A	0·061
Second	Paraffin oil	0·068
Third	,, ,,	0·060
Second	,, ,, + 5% copper oleate	0·063
Third	,, ,, + 5% sodium stearate	0·060
Second	,, ,, + 5% lead stearate	0·058
,,	,, ,, + 5% lead oleate	0·058
,,	Olive oil	0·057
,,	Paraffin oil + 1% lauric acid	0·052
Third	,, ,, ,, ,,	0·054
,,	Shell PE 6	0·050
Fourth	,, ,,	0·053
Third	Esso 885 pale	0·052
Fourth	615 graphite in oil	0·047
,,	Castor oil	0·045
,,	Lanoline	0·041
,,	Camphor flowers (natural)	0·038
	(*b*) Aluminium-annealed strip	
First	Clean and dry	0·092
,,	Paraffin oil	0·081
,,	Palm oil	0·066
,,	Paraffin oil + 1% oleic acid	0·059
,,	615 graphite in oil	0·055
Second	Clean and dry	0·101
,,	,, ,, ,,	0·101
,,	,, ,, ,,	0·100
Third	,, ,, ,,	0·099
Second	Paraffin oil	0·087
,,	Vac. R.O 546	0·082
Third	Palm oil	0·066
,,	,, ,,	0·064
Fourth	,, ,,	0·069
Third	Paraffin oil + 5% sodium oleate	0·059
,,	,, ,, + 5% lead oleate	0·056
,,	Castor oil	0·057
Second	Paraffin oil + 5% lead oleate + 0·6% S	0·049
Fourth	Lanoline	0·025

The repeatability of the results is clearly shown in this table and the generally low coefficient is demonstrated.

From a large number of tests such as these, the following conclusions were reached:

(1) A high coefficient of friction (0·08 to 0·14) is usually associated with a rough roll and shows a bright torn surface.

(2) A medium coefficient (0·06 to 0·08) generally gives the optimum results. A good roll finish is required, since it appears to have the effect of bending over the asperities and smearing them over the surface, with minimum tearing action, the surface having a burnished appearance with a low Talysurf roughness value.

(3) Some lubricants are better than others: a good lubricant is one which both tends to allow the burnishing action of a smooth roll, and also acts somewhat like a cutting fluid when slight tearing starts, by tending to separate the junctions.

(4) Generally, while the smoothness in the longitudinal direction of the strip (where relative motion occurs) improves, that in the transverse direction, *i.e.* along the roll barrel, where there is practically no relative motion, does not, and with higher friction tests roughness tends to increase in the latter direction as it decreases in the former.

(5) Lubricants which give low coefficients of friction (0·03 to 0·05) leave the strip matt and dull. In many cases there is serious surface damage, not so much by ploughing action, but by tearing of particles out of the surface. The explanation of this has not yet been found, and more experiments are needed.

MECHANISM OF FRICTION IN METAL FORMING

The foregoing evidence—and it is supported by indirect results obtained from other processes—suggests that some modification is required to the friction mechanism proposed for boundary conditions between elastic bodies. The explanation would appear to be found in the fact that if one of the bodies is either about to deform or is deforming under a high normal stress, the tangential shearing stress forms only one component of a complex stress state, and accordingly only a small stress is necessary in the tangential direction.

If k is the yield stress of the deforming material in simple tension or compression, the Mises yield criterion gives $s^2 = (k^2 - p^2)/3$ for plane strain deformation, where s is the local shear stress and p the normal pressure (Fig 2). Accordingly, if p is small compared with k, *e.g.* as in normal friction experiments, then $s \sim k\sqrt{3}$, but if by the nature of the forming process, p is the predominant stress producing deformation, *e.g.* as in rolling, forging, etc., s will be comparatively small. The asperity will rapidly work-harden; will partly be smeared over the surface and partly forced into the deforming mass. This and the general deformation (supposing no lubricant is present) will cause the comparatively unworked material immediately on either side to be pushed into contact with the die surface. The movement would not, in general, be uniform, so that the mechanism would be repeated with fresh asperities.

The above mechanism has been suggested by Bowden and Tabor[3] for slider experiments between elastic bodies, but does not appear to have been

developed for the case of plastic deformation, where it clearly applies.

As soon as the general mass of deforming material has been work-hardened to some extent, the difference in the value of the yield stress between the maximum possible in the asperities and the average in the mass will be reduced: accordingly, the pressure p required to cause general deformation will be much nearer to that required to cause deformation in the asperities. The coefficient of friction for a work-hardened material should then be somewhat less than for an annealed one, because in the latter the shear stress s

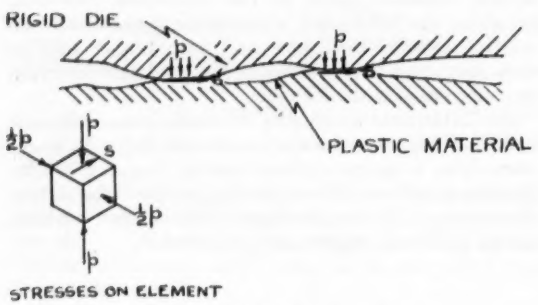


FIG 2

FRICTION WITH A DEFORMING SURFACE

would be relatively greater; for if k_a is the tensile yield stress of the main mass of the material, k_w that of the asperities, then $p \longrightarrow k_a$ and approximately $s^2 = (k_w^2 - k_a^2)/3$ which may be large for a material with a wide work-hardening range.

Obviously, the friction would be dependent upon the roughness of the die surface to a great extent because the plastic surface is continually deforming to fit itself into the asperities on the die, and these will tend to plough their way through the deforming metal.

If now a lubricant is present between the surfaces, it will tend to be trapped between the asperities, and intense pressures will be built up in the film, which will help to prevent contact between the surfaces. In cold rolling there is clear evidence that lubricant is carried through the roll gap, and a " good " lubricant will be one whose viscosity, adherence, etc., are not adversely affected by very high pressures.

The mechanism suggested here would explain a good many of the observations which have been described.

REQUIREMENTS OF LUBRICANTS IN METAL-WORKING PROCESSES

From the general conclusions given above it will be seen that a good lubricant should provide a sufficiently thick film that only the largest asperities break through it and are rubbed and smeared over by the relative motion. A good lubricant should also prevent excessive welding of the deforming material on to the die. The roughness of the die surface will clearly be important, since any asperities will inevitably be locked into the plastic metal and will give rise to the ploughing action described by Bowden and Tabor as being the other main constituent of the friction between metallic surfaces. With smooth, polished surfaces (tests with rolls show that " smooth " means a Talysurf h_{av} of less than 10 microinches) the ploughing term is unimportant.

If, as would appear from tests, lubricants can and are carried through the roll gap in cold rolling (there is evidence that they are similarly carried through in wire-drawing), they must be subjected to extremely high pressures, and it is therefore relevant to ask what happens to their physical properties at such pressures. Little appears to be known about the viscosity of liquids at high pressures, and the observation that viscosity (when judged on atmospheric pressure values) bears no relation to the frictional behaviour in the roll gap may be explained by the fact that some lubricants may be more affected than others.

A programme of experiments to determine the dependence of physical properties both on pressure and temperature might elucidate many of the unexplained results in industrial and laboratory tests and lead the way to a closer insight into the real requirements for lubricants in metal-forming processes.

References

1 *Proc. roy. Soc.*, 1952, **A212**, 439 to 520.
2 " Properties of metallic surfaces. 1953." Inst. Met. Monograph and report series No. 13.
3 Bowden, F. P., and Tabor, D. " The Friction and Lubrication of Solids." Oxford: Oxford Clarendon Press, 1950.
4 Forrester, P. G. *Proc. roy. Soc.*, 1946, **A187**, 439.
5 McLellan, G. D. S. *J. Inst. Met.*, 1952, **81**, 1.
6 Ford, H., and Ellis, F. *J. Iron St. Inst.*, 1952, **171**, 239.
7 Baron, H. G., and Thompson, F. C. *J. Inst. Met.*, 1950, **78**, 415.
8 Watts, A. B., and Ford, H. *Proc. Instn mech. Engrs, Lond.*, 1952, **B1**, **10**.
9 Hill, R. *Phil. Mag.*, 1950, **41**, 733.
10 Orowan, E. " The Rolling of Metals," pp. 154–62. London: Chapman and Hall, 1950.
11 Bland, D. R., and Ford, H. *J. Instn mech. Engrs, Lond.*, 1948, **159**, 144.

SOME OBSERVATIONS ON CONDITIONS OF LUBRICATION IN WIRE-DRAWING DIES*

By D. G. CHRISTOPHERSON, O.B.E., H. NAYLOR, and J. WELLS

INTRODUCTION

FROM the point of view of lubrication, the wire-drawing die presents a serious problem. The pressure between the wire and the die is of the same order as the yield stress in the wire, often many tons per square inch, and the relative velocity of the surfaces may be several thousand feet per minute. Under such conditions, it is not to be expected that any boundary or extreme pressure lubricant will be entirely successful in preventing wear. In fact, wear of the die, leading to the necessity of changing dies rather frequently, is one of the factors limiting the rate at which wire can be produced. The wear can be regarded as being of two kinds:

(*a*) Ringing wear, which takes place at or about the point where the diameter of the die equals the diameter of the incoming wire, and thus produces a ring on the die surface.

(*b*) Wear of the parallel or "sizing portion." The wear is usually less severe, considered in terms of the amount of material removed, than the ringing wear, but may be decisive in fixing the life of the die if a wire having a very accurately specified final diameter is required.

A good deal of work has been done in the past few years, with a view to reducing die wear. Some workers [1,4] have concentrated on observing the die friction, either by measurements of the drawing force, as a function of back-pull, or by some other method. Some direct observations of wear have also been made [6] with the primary intention of comparing existing wire-drawing lubricants. Much of the work suggests that the state of affairs is in many cases intermediate between what would ordinarily be regarded as boundary lubrication, on the one hand, and fluid or hydrodynamic lubrication, on the other.

Coefficients of friction as low as 0·03 to 0·06 are often encountered, and the quantity of lubricant passing through the die is much greater than can be accounted for by the few molecular layers which are required for boundary lubrication. If some additional steps could be taken to increase still further the flow of lubricant through the die, true fluid lubrication might be established, and very substantial reductions in wear obtained. This can be achieved if the lubricant is supplied to the die inlet at high pressure. Indeed, if the pressure is of the same order as the yield stress of the wire, the deformation will be started by fluid pressure only, without any metal-to-metal contact between die and wire.

FORCED LUBRICATION OF DIE

It might be thought that to supply the lubricant at this pressure would be a considerable undertaking, but this is not so. Some years ago MacLellan and Cameron pointed out that if the wire as it approached the die passed through a tube of internal diameter slightly larger than the wire diameter leading into a pressure tight chamber on the inlet side of the die, a pressure would be generated by viscous action. They regarded the device as relevant mainly to the separate question of swarf removal; aqueous lubricants were employed in tubes having fairly large clearances, and the pressures generated were of the order of a few atmospheres. None the less, there is no reason why the same principle should not be employed to generate pressures thousands of times larger, though it will

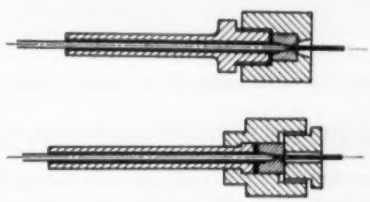


FIG 1

TYPICAL ARRANGEMENTS OF INLET TUBE AND DIE

then be necessary to use small clearances with fairly heavy oils as lubricants. The chamber between tube and die has no purpose in this application, and either of the arrangements shown in Fig 1 may be employed.

Experiments on these lines have been proceeding at Leeds for the past two years. It was quickly found that the basic idea underlying this suggestion was substantially correct. Employing mineral oils as lubricants with either of the arrangements shown in Fig 1, the pressure at the entrance to the die rises as the drawing velocity is increased, until the value necessary to cause deformation of the wire is achieved. Up to this stage, the flow of oil through the die is very small, and the die friction is high. If the drawing velocity is further increased, the flow of lubricant through the die rises rapidly, and the drawing force decreases sharply. The pressure at inlet to the die, however, remains about constant, since this is now fixed almost entirely by the strength of the wire. Once this condition has been reached, considerable variations of speed are possible without any substantial effect on the drawing force. Ultimately, how-

* MS received 8 January 1954.

ever, increasing speed leads to increased friction, as it does in any other example of fluid lubrication, for example in a journal bearing.

The investigation of the pressure generating effect of the tube has been carried to a stage at which it is possible to make a fairly accurate theoretical prediction of the dimensions necessary to produce a specified pressure with any given lubricant. This will be published elsewhere, and the following describes some of the physical results which have been found to follow from the improvement in the conditions of lubrication at the die.

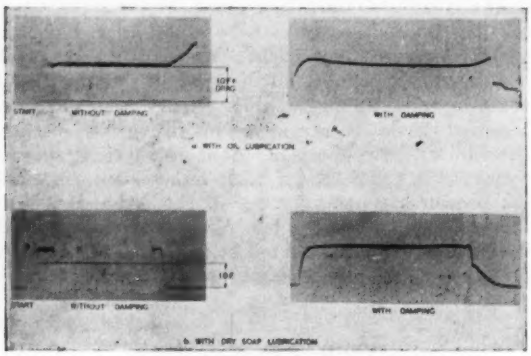


FIG 2

OSCILLOGRAPH RECORDS OF DRAWING FORCE

DRAWING FORCE OBSERVATIONS

The force required to pull the wire through the die is plainly a measure of the work done per unit (final) length of wire. In the absence of any friction, it is equal to the work done per unit length in pulling out a tensile specimen to the same reduction of area in a tension machine. This quantity is the "ideal" drawing force. Unfortunately the ideal drawing force depends to some extent on the speed of drawing, as most materials are stronger when pulled out rapidly than they are when pulled slowly. The term "dynamic ideal drawing force" may be used to refer to the work done per unit length in pulling out a specimen to the same reduction of area at the same rate-of-strain as occurs in the drawing operation.

The observed drawing force in the set-up in Fig 1 contains three components:

(1) the "dynamic ideal drawing force" as described above;

(2) the friction drag from the inlet tube as calculated by hydrodynamic theory;

(3) the die friction.

Fig 2 shows a record of the variation of drawing force during a run starting from rest and finishing at rest. During the constant speed portion of the run, the dynamic ideal drawing force and the estimated tube drag are constant, and are marked on Fig 2 (*a*). It will be seen that there is very little drawing force left to be accounted for by die friction (3) above for most of the run. At starting, however, fluid lubrication has not been established in the die, and die friction is large. Similarly, the film breaks down just before the machine stops. Fig 2 (*b*) shows the corresponding result for soap lubrication.

This evidence suggests that the die friction at the speed of normal running is very small and that fluid lubrication has been established. A number of additional tests have been made to verify this suggestion.

ELECTRICAL RESISTANCE OBSERVATIONS

In the first place an attempt was made to measure the electrical resistance of the lubricating film. The method employed is shown in Fig 3. A 2-volt battery passes a current through a resistance, through the die-wire interface, and back along the wire. A cathode-ray oscillograph is then arranged to display the voltage across the interface. If the resistance at the interface is much larger than the rheostat resistance this voltage is nearly equal to the applied voltage. If, however, there is a metallic contact anywhere, an almost zero voltage—a "break-down"—will be recorded. Fig 4 (*a*) and (*b*) are photographs of the traces obtained. It is evident that at 200 f.p.m.

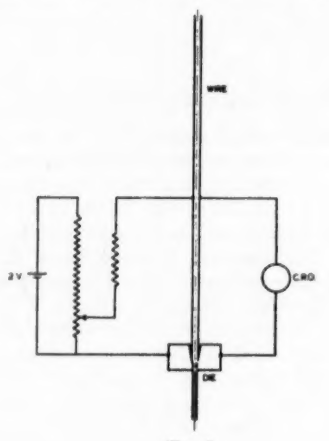


FIG 3

CIRCUIT DIAGRAM FOR DIE–WIRE INTERFACE RESISTANCE MEASUREMENTS

metal-to-metal contacts (when the resistance falls to zero) occur frequently. At 600 f.p.m. they do not occur at all,* the average resistance being large.† Fig 4 (*b*) shows a similar record obtained with a soap lubricant. It is fair to point out that the average is again very high—even higher than with oil—but even at 600 f.p.m. there are still a few breakdowns.

Fig 4 (*b*) shows also a curious feature. When the

* There were two breakdowns early in the run at this speed.

† Dr F. P. Bowden [2] considers that the resistance of a thin but complete boundary lubricating film is of the order of a fraction of an ohm.

resistance of the lubricating film is large, the oscillograph tracer should appear as a single horizontal line. It should never rise above the battery voltage. It is plain in the records of Fig 4 (*b*), however, particularly at higher speeds, that higher voltages are repeatedly being observed. It may be that this phenomenon is electrical in character, due to some imperfection in the oscillograph, but it is also possible that at a

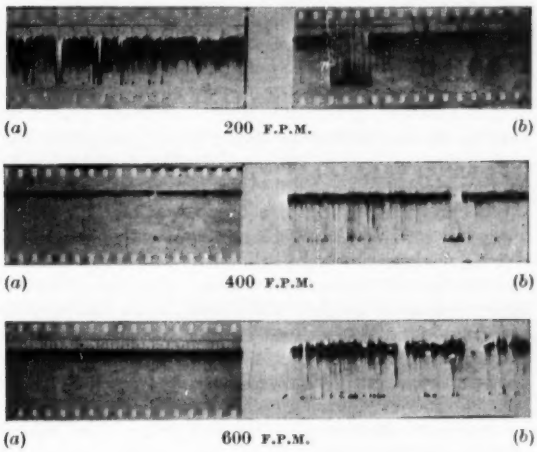


FIG 4
(*a*) OIL LUBRICATION AND (*b*) SOAP LUBRICATION

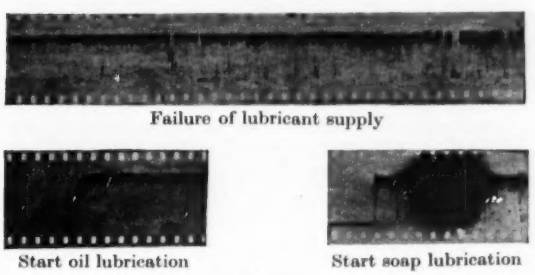


FIG 5

metallic contact a high temperature is generated, and accordingly a considerable thermo-electric e.m.f. will be added to the battery voltage and recorded on the oscillograph.

In Fig 5 are shown the records obtained: (*a*) when an inadequate supply of oil is provided for fluid lubrication by allowing the oil reservoir to empty itself; (*b*) at start with oil lubrication, it takes a few seconds for the pressure to be built up; and (*c*) with soap lubrication the rise of resistance is instantaneous, but serious breakdowns persist for some time.

OBSERVATIONS OF WIRE DISTORTION

Another quite different technique can also be employed to give a measure of the friction acting on the wire as it passes through the die. This method was first employed by Taylor and Quinney.[5] In their work two semi-circular rods, on the flat faces of which rectangular grids had been inscribed, were drawn

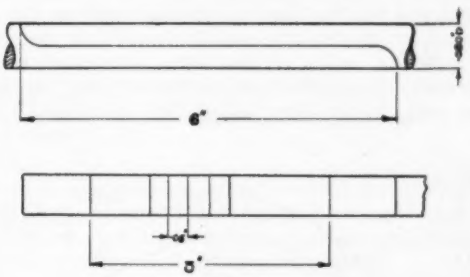


FIG 6

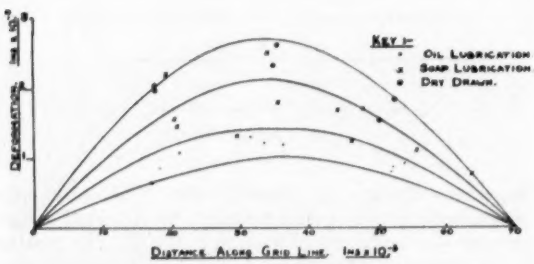
together through a circular die. The originally rectangular grid was then found to be distorted. The greater the coefficient of friction in the die, the greater is the distortion of the wire, but it is probably not true that if the coefficient of friction were zero, the wire would be quite undistorted. Hill's theoretical researches [3] into the plastic behaviour of a sheet drawn through a frictionless conical die have shown that even in this case some distortion occurs. Unfortunately, it has not proved possible to do the mathematics necessary to solve the same problem for the circular wire.

So that drawing could more closely approximate practical speeds, the technique described here differs a little from the above. A " split " wire was therefore made up by milling off half the section of a circular wire near one end, and soldering to it a similar portion, also reduced to a semicircle by machining, transverse lines being inscribed on the flat surface before soldering as in Fig 6. The wire thus prepared is then drawn in the usual way. It was important for the wire to be drawn once only, so that, among other things, an observation could be made of the random variations in friction which occurred at different points in the wire, and such variations might be largely ironed out by repeated draughts. Accordingly, the distortion

FIG 7

observed was fairly small in all cases. Typical examples of the distorted wires are shown in Fig 7 (*a*) and (*b*). The extent of these distortions can, however, be measured under a microscope, and the results obtained are shown in Fig 8. In this figure the horizontal scale is one hundred times actual size, and the vertical scale one thousand times full size, so the

extent of the distortion is magnified ten times. The distortion shown in the lowest curve—that for fluid lubrication at 400 f.p.m.—is very close to the ideal that would be obtained with zero die friction. The results show little variation when fluid lubrication is employed (all the observations fall between the two lowest curves), but with soap-lubrication the distortion at different points on the wire varies over a considerable range, the mean distortion being about 70 per cent greater than under fluid conditions. The



400 f.p.m.

FIG 8

" dry " observations, which fall between the two upper curves, were obtained by drawing without any added lubricant, and the distortion is about twice the ideal distortion. Moreover, it must be said that although the wire and die were cleaned with methylene trichloride before drawing, it is not improbable that even in these cases traces of previously employed lubricants remained.

CONCLUSION

It is plain that these different experimental methods all suggest the same conclusion, that fluid lubrication can be established in the die and that, if established, it will provide more consistent and more controllable behaviour. Furthermore, the factor which limits operating speed is probably, in most cases, the die surface temperature. This is related directly to the die friction—the viscous friction in the tube contributes very little to it—and thus a useful purpose is served by reducing die friction even if the total drawing force is not thereby reduced.

At the same time, it must be admitted that it has not so far been possible to observe the quantity of the first importance—the wear in a tungsten carbide die. Some observations have been made of wear in steel dies, and these confirm the view that fluid lubrication will be effective in reducing wear, but these cannot be said to be conclusive, as there is no proof that the mechanism of wear in tungsten carbide is the same as that in steel.

The problem of the direct observation of wear in tungsten carbide is not an easy one experimentally. Actual operational comparisons require large quantities of wire for each observation. The use of radioactive tracer methods is attractive, but is not easy to put on a quantitative basis. Basically the difficulty is that, in most wear tests, the statistical variation between apparently similar experiments seems to be large, and thus convincing results can be obtained only by frequent repetitions. A rapid and simple means of detecting and measuring incipient wear would be of the greatest value not only in this application but also in many others, and it is this problem which is now receiving attention.

References

[1] Baron, H. G., and Thompson, E. C. *J. Inst. Met.*, 1950, **78**, 415.
[2] Bowden, F. P., and Tabor, D. " The Friction and Lubrication of Solids." London : Oxford University Press, 1950.
[3] Hill, R. " Mathematical Theory of Plasticity." Oxford : The Clarendon Press, 1950.
[4] MacLellan, G. D. S. *J. Iron St. Inst.*, 1932, **81**, 1.
[5] Taylor, G. I., and Quinney, H. *J. Inst. Met.*, 1932, **49**, 178.
[6] Wistreich, J. G. *J. Iron St. Inst.*, 1951, **167**, 162.

SOME LUBRICATION EFFECTS IN DEEP DRAWING OPERATIONS*

By E. M. LOXLEY and P. FREEMAN

SUMMARY

The importance of correct lubrication when forming metal components by deep drawing and related operations has long been realized. Even so, there are many gaps in the knowledge of the part played by lubrication in such operations, and this paper outlines recent attempts to close these gaps by experimental investigations carried out in the Engineering Departments of the University of Sheffield.

INTRODUCTION

THIS paper is divided into three sections, each section dealing with the influence of lubrication on a particular cylindrical drawing operation.

In the first section it is shown that the so-called anomalous drawing properties of aluminium sheet, *i.e.* the fact that under certain conditions the harder tempers of aluminium sheet can be formed into deeper pressings of a certain diameter than the annealed material, are entirely a lubrication effect, and can be suppressed or made more pronounced merely by the choice of applied lubricant.

The influence of lubrication on the stretch-forming and cylindrical drawing of steel sheet is discussed in the second section. In the third section some effects of lubrication on the ironing of metal cups are discussed, and it is shown that for optimum ironing conditions it is desirable to employ a good quality drawing lubricant between die and outer cup surface. In drawing operations it is shown that punch side lubrication is generally undesirable and that the optimum drawing conditions result from the use of an efficient lubricant on the die side of the blank and no lubricant whatsoever on the punch side of the blank. The effect of flange lubrication, *i.e.* lubrication of the material in contact with the blank holder, has not as yet been fully considered.

THE ANOMALOUS DRAWING PROPERTIES OF ALUMINIUM

During the early stages of work carried out in the University of Sheffield towards the establishment of an industrial test for the drawability of sheet metal, a study was made of the principal strains occurring during the drawing of a cylindrical cup.[1] For this purpose tools were designed and built to accommodate a 2·00-inch diameter punch with a flat head and a profile radius of 0·25 inch (Fig 1), and to draw materials with thicknesses within the range 0·034 to 0·044 inch. These tools, which incorporated a positive clearance method of blank holding (overhead clearance = 0·002 inch), were capable of being mounted in the compression space of a universal multi-lever testing machine, and consequently drawing could be performed at relatively slow speeds but under very carefully controlled conditions. In the preliminary stages of development it was found that the use of this apparatus in its original form could differentiate quite clearly between the drawing qualities of different materials and different lubricants.

When drawing cups from annealed and half-hard aluminium in this apparatus, however, it was noticed that the harder material seemed to possess the better drawing properties in that a larger blank could be formed into a cup without fracture occurring. Inquiries revealed that this fact was known to industry

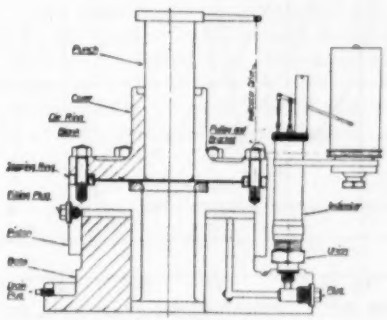


FIG 1

AUTOGRAPHIC SUB-PRESS WITH SPACING RING

but that it was true only for certain types of pressing and was definitely not so for pressings in which stretch-forming, as opposed to, or in combination with, radial drawing occurred.

In an attempt to find some possible explanation of this phenomenon, it was decided to compare the performance of different metals when drawn with (*a*) a hemispherical-headed punch with a profile radius of 1·00 inch and (*b*) a flat-headed punch (profile radius = 0·125 inch) similar to that which had been used hitherto. Tests were carried out on blanks lubricated with a mixture of graphite-in-tallow (1 : 3 by weight) and prepared from aluminium (99·5 per cent commercial purity), 70/30 brass, electrolytic copper, rimming steel, and several aluminium–magnesium alloys, all in annealed and several work-hardened tempers. The nominal thickness of all the sheets of metal used was 0·036 inch and the drawing speed adopted for the tests was 0·1 inch per minute. These tests showed that all the materials exhibited

* MS received 24 November 1953.

the peculiarity that the soft metal drew better, *i.e.* possessed a bigger safe drawing ratio, with the hemispherical punch than with the flat one, while the reverse was the case for the work-hardened materials, particularly if the amount of pre-strain was at all appreciable.[2] This peculiarity or anomaly in the drawing of sheet metal is evidently tied up with the stress–strain–strength properties of materials. While it is not yet possible to predict the maximum safe drawing ratio for any particular combination of punch form, lubrication, and material, it is possible to predict the limiting thickness strain in a flat-headed cup using a theory based on the strain hardening characteristic

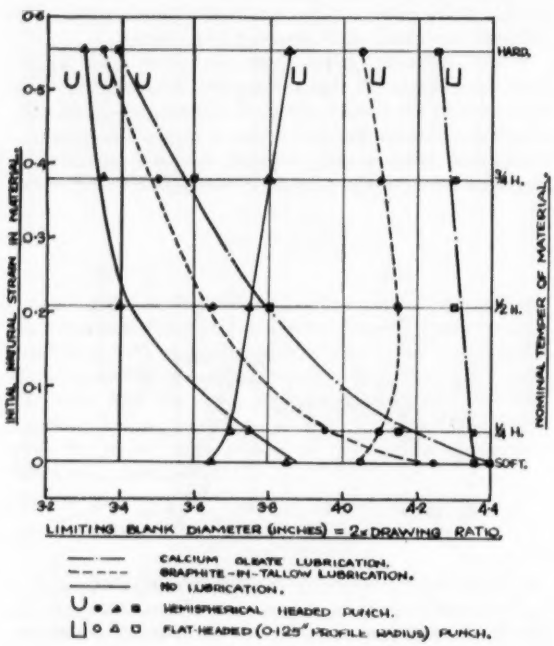


FIG 2

ANOMALOUS DRAWING PROPERTIES OF ALUMINIUM

of the material being processed.[3] (Because of the uncertainty of the stress distribution in the material forming the dome or crown of a cup, it is not possible to apply the present theory to any shape of pressing other than the flat-headed one with a relatively small profile radius between crown and skirt.)

In the drawing of aluminium, however, a further anomaly was observed in that when using a flat-headed punch the work-hardened tempers gave results at least equal to and generally better than the annealed material. As previously mentioned, this fact was already known to the drawers, and in their experience had occasionally been suppressed by changing the lubricant used during the forming process. It was therefore decided to study in more detail the influence of lubrication on this particular anomaly, and two further series of tests were made using the same stock of aluminium sheet and maintaining the same experimental conditions as had been used throughout the earlier work. In the first of these test series, unlubricated aluminium blanks were tested after both blanks and apparatus had been thoroughly degreased with carbon tetrachloride; in the second series the blanks were lubricated with calcium oleate, a lubricant which in other tests had proved one of the most efficient in reducing press loads required to form a cup of a particular shape and size.

The results of these tests, together with those made on blanks lubricated with graphite-in-tallow, are shown in Fig 2. It will be noticed that under all the lubricating states considered the anomaly previously assigned to material effects is present. The second anomaly, *i.e.* the fact that when using a flat-headed punch the work-hardened tempers of aluminium draw better than the annealed material, is completely followed by the unlubricated material and partly so by the graphite-in-tallow lubricated blanks, while the tests using calcium oleate as lubricant show the aluminium behaving in the same manner as all other materials tested in the course of this work.

As a result of these tests it seems a reasonable conclusion that the anomalous behaviour of different tempers of sheet aluminium when drawn with a flat-headed punch is a lubrication effect, and that its suppression probably demands the use of a very efficient (and possibly solid) lubricant despite the relatively low press loads involved.

EFFECT OF PUNCH FORM AND LUBRICATION IN DEEP DRAWING OPERATIONS

Long experience with the deep drawing of sheet metal has shown that provided material clearances and/or blank holding pressures are kept within certain prescribed limits, failure of a circular blank to draw successfully into a cylindrical cup generally results from excessive thinning of the material which is in contact with the punch head, *i.e.* failure usually occurs in the primary neck *I*, shown in the typical thickness strain distribution curve, Fig 3. Systematic experimental studies under identical conditions of blank holding and die profile and clearances have revealed that the maximum safe drawing ratio for any given material is a function of the punch profile and the applied lubricant.

As a result of an investigation[4] carried out at Sheffield, there is now available a workable theory to predict (*a*) the strains which develop in the walls of a cylindrical pressing and (*b*) the press loads required to produce such a pressing provided we know (1) the strain-hardening characteristics of the material being processed and (2) the state of lubrication on the blank.

Attempts, however, to explain the behaviour of metal over the punch head, *i.e.* in the stretch formed region (Fig 3) during a forming operation, have not as yet been too successful. In such a region the stress system in the material being processed is essentially one of biaxial tension. Little is known of the behaviour

of metals under such a stress state, and in an attempt to close this gap in knowledge a group of related research programmes are now in progress at Sheffield.

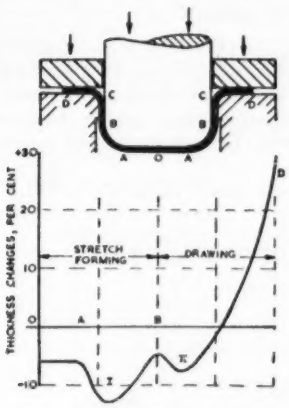


FIG 3

TYPICAL THICKNESS DISTRIBUTION CURVE FOR A DEEP DRAWN SHELL

These investigations may be briefly described as follows :

(1) A study of the flow and failure characteristics of sheet metal under biaxial tensile conditions when deformed without frictional restraint by means of hydrostatic pressure.

(2) A similar study to (1), except that friction is introduced, and the shape of the pressing is governed by stretching it over a large hemispherical-headed punch.

(3) An investigation into the influence of lubrication and punch form on the flow and fracture characteristics in the stretch formed region of cold drawn cylindrical shells.

The first part of this investigation (the bulge test) is outside the scope of this paper, but full details of its progress are given elsewhere.[10]

Preliminary experiments in the second and third parts of this work throw light on the importance of lubrication in both the stretching and drawing operations, and these are given in detail in the following passages.

Stretch Forming with a Solid Punch

The apparatus (Fig 4) used for this investigation is of simple, robust construction. The hollow steel cylinder *A* of 10-inches bore diameter supports the die ring *B* having a throat diameter of 10 inches and a profile radius of $\frac{3}{4}$ inch. The circular sheet (20 s.w.g.) specimen *C* is held rigidly around its periphery by being clamped between the base *A* and the top plate *D*. This assembly is mounted centrally on to an autographic load recorder (a hydraulic diaphragm) *E* clamped to the lower bolster of a hydraulic press.

The hemispherical-headed steel punch, *F*, of 5·00 inches profile radius, is mounted coaxially with the specimen and clamping tools and rigidly secured to the upper press bolster.

Several steel specimens each 13·0 inches diameter were cut from 20 s.w.g. killed steel sheet. A clamping rim was then formed on each of these blanks by placing them one by one in position in the clamping tools and tightening the appropriate fixing bolts. On removal from the apparatus, each specimen was in turn degreased in trichlorethylene, pickled in a nitric acid solution, washed in water, and dried. A circular grid was then scribed in ink on the surface of each specimen which would face downwards when the latter was reassembled in the clamping tools. The grid consisted of a series of circles increasing in radius by 0·2 inch and concentric with the centre of the specimen found by a simple construction using the formed ring for reference. The exact spacing of these scribed rings and the thickness of each specimen were then determined from travelling microscope and micrometer measurements respectively.

Partial pressings, *i.e.* unbroken pressings to different polar heights at a press ram speed of approximately 6 f.p.m., were then made for (*a*) blanks and punch lubricated with graphite-in-tallow and (*b*) blanks and punch thoroughly cleaned and degreased with trichlorethylene.

The radial spacing of each scribed line and the thickness of each specimen at eight equal intervals

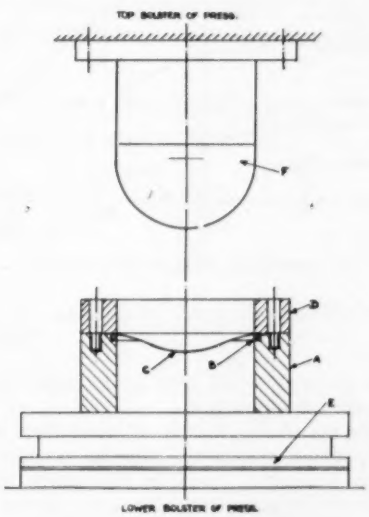


FIG 4

STRETCH FORMING TOOLS WITH 10-INCH CENTRE PUNCH

around each scribed line were then measured, and from these the distribution of thickness strain over each partial pressing (Fig 5) was obtained.

The effect that friction has upon the development of thickness strain is clearly seen from Fig 5. Even with graphite-in-tallow lubrication the maximum strain is

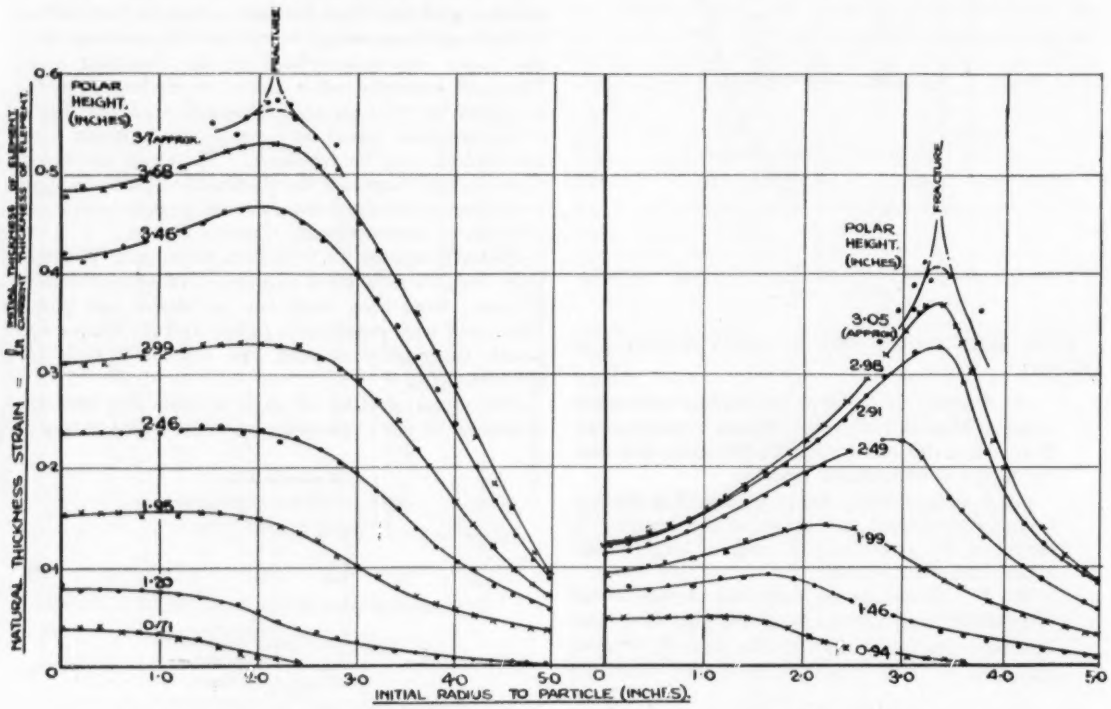
not at the pole or centre of the pressing as would probably be the case if there were no friction (cf. the bulge test). When no lubricant is used the effect is more marked and the position of maximum strain moves further away from the centre of the pressing as the punch penetration increases, ultimately to form a distinct "neck" in the material. In both Figs 5 (*a*) and (*b*) the uppermost complete curve shows the strain immediately before fracture, and it will be noticed that with lubricant a much greater overall strain is attained, while with no lubricant the polar strain is almost suppressed.

Another interesting feature of these tests is shown in Fig 6, which relates the angular position of the maximum thickness strain to the depth of punch penetration (or polar height). Also shown in this diagram is a curve giving the angle of embrace of material over the punch head as a function of the polar height of the pressing. This latter curve is based on the assumption that the material leaves the punch along the common tangent between punch and die (see inset to Fig 6). It will be observed that with lubricated blanks the point of maximum thickness strain occurs in some part of the material still over the punch head, while with unlubricated blanks the angular position of maximum thinning in the material is almost identical with the point where the material leaves the punch.

The Influence of Punch Form and Lubrication in a Deep Drawing Operation

This part of the investigation concerns the development of principal strains in "limiting size" and "oversize" blanks of killed steel when drawn into 4·0-inch diameter cups under positive clearance conditions with (1) a hemispherical-headed punch and (2) a flat-headed punch with a profile radius of 0·125 inch.

The apparatus used is shown in Fig 7. The punch *A* of 4·00 inches diameter is secured to the top bolster *B* of a hydraulic press and mounted coaxially with the die holder *C* secured to the bottom press bolster *D*. The die ring *E* has a throat diameter of 4·100 inches and a profile radius of 0·25 inch. When the top plate *F* is securely bolted to the die holder *C*, the clearance between their common faces is 0·002 inch. When in operation, the specimen blank *G* is centred above the die on the relevant face of the die holder, and inserts of material cut from the same stock as the specimen are placed between the annular side faces of the die holder and top plate, thus giving an overhead clearance of 0·002 inch to the specimen.



(*a*) Lubrication with graphite-in-tallow (*b*) No lubrication

FIG 5

EFFECT OF LUBRICATION ON THE DISTRIBUTION OF THICKNESS STRAINS IN STEEL SPECIMENS STRETCH-FORMED WITH A HEMISPHERICAL-HEADED PUNCH

The material used for this investigation was nominally 20 s.w.g. killed steel sheet, and circular blanks were prepared from it and suitably scribed with concentric circles in accordance with long established procedure.[1]

Tests were then carried out to determine the maximum size of blank which drew satisfactorily (the

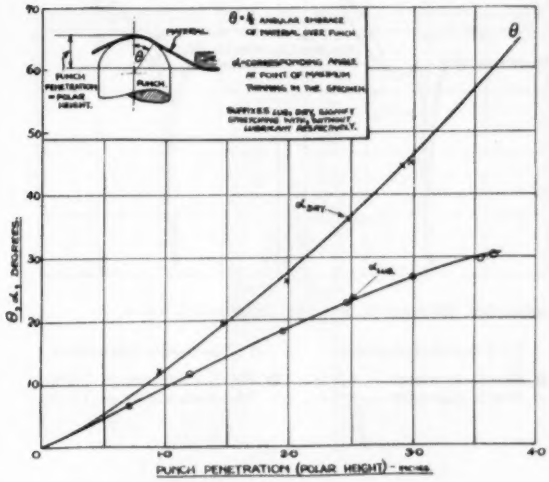


FIG 6

STRETCH FORMING OF STEEL WITH HEMISPHERICAL PUNCH

Relationship between angular position of maximum thinning in specimen and depth of punch penetration into original plane of specimen.

" limiting " size) with each punch and with each of the following lubricating states :

(*a*) total blank lubrication with graphite-in-tallow ;

(*b*) no lubrication on trichlorethylene degreased blanks and tools ;

(*c*) graphite-in-tallow lubricant applied to die-side of blank only ; and

(*d*) graphite-in-tallow lubricant applied to punch-side of blank only.

Thickness strain distribution curves [1] were obtained for each of the resultant limiting blank sizes and for blanks larger in diameter by 0·1 inch (fractured " oversize " blanks), and these are given in Figs 8 (*a*) to (*h*).

It will be noticed that in all cases the position and magnitude of maximum strain on satisfactory pressings, the position of fracture on broken pressings, and the limiting blank size are all functions of the state of lubrication on the blank. Furthermore, with the hemispherical-headed punch, the so-called primary neck (*I*—Fig 3), *i.e.* the point of maximum thinning caused by stretching and bending under tension over the punch profile, does not always determine the point of fracture. In actual fact, with absence of punch-side lubrication, the point of fracture on " oversize " blanks occurs at a point in the blank corresponding to a point in the wall of the finished pressing quite remote from the primary neck.

The use of lubrication only on the die-side of a blank, leads to the greatest safe drawing ratio (see Table I) with either of the punches used, while

TABLE I

Summary of Tests Showing Influence of Punch Form and Lubrication on Limiting Blank Sizes when Drawing 20 s.w.g. Killed Steel Sheet with Positive Clearance (5·5 per cent) Blank Holding

Limiting blank diameter, inches	Punch profile	State of lubrication *	Maximum drawing load, tons	Maximum thinning strain, %	Comments
7·9	Flat	Complete	12·9	17·7	Maximum thinning in neck *I* (Fig 3)
8·5	Hemispherical	Complete	13·3	21·8	Maximum thinning in neck *I*
7·6	Flat	None	13·2	14·7	Maximum thinning in neck *I*
8·3	Hemispherical	None	13·7	16·7	Failure on " oversize " blanks in wall of cup
8·1	Flat	Die side only	13·3	20·0	Maximum thinning in neck *I*
8·9	Hemispherical	Die side only	14·5	13·0	Maximum thinning in neck *II* (Fig 3)
7·6	Flat	Punch side only	13·0	12·5	Maximum thinning in neck *I*
8·1	Hemispherical	Punch side only	12·7	21·2	Maximum thinning in neck *I*

* Where lubricant was used this was a mixture of one part graphite in three parts of tallow by weight.

lubrication of the punch-side alone is inferior to or at least no better than no lubricant at all. This suggests that in cases where large single stage reductions are

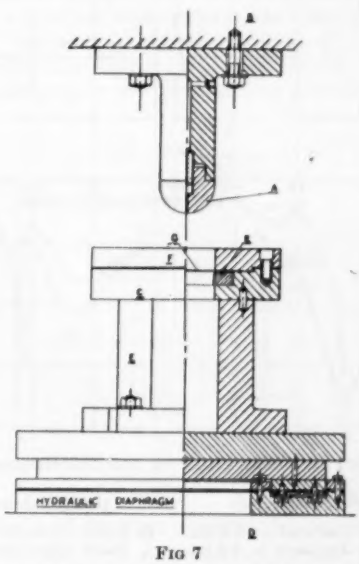
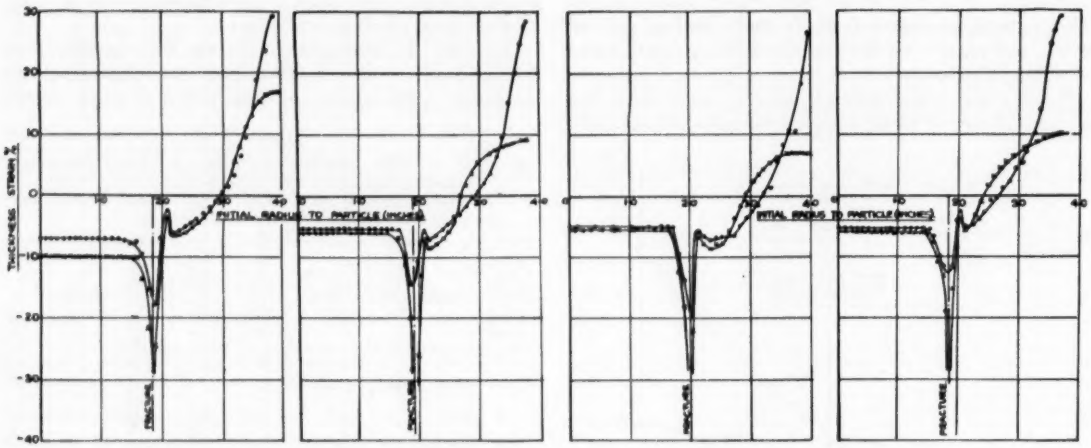


FIG 7

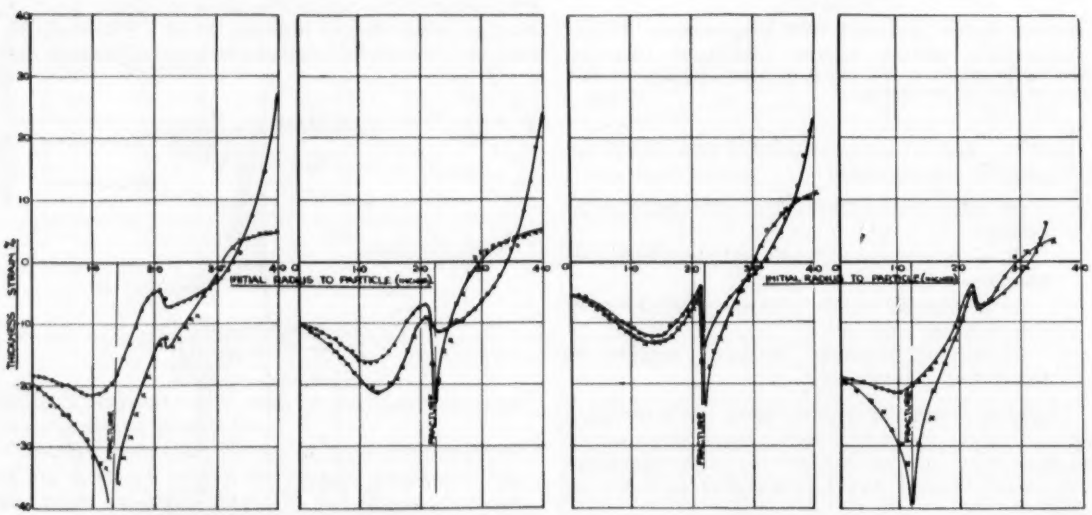
DRAWING TOOLS FOR 4·0-INCH DIAMETER CUPS

required in cylindrical drawing operations, a high coefficient of friction between the punch and the material will be advantageous, while the reverse is the case between material and die.



EFFECT OF LUBRICATION ON THE DISTRIBUTION OF THICKNESS STRAINS IN FLAT-HEADED STEEL CUPS

(a) *Full lubrication*	(b) *No lubrication*	(c) *Die-side lubrication*	(d) *Punch-side lubrication*
● Blank diameter = 7·9 in.	● Blank diameter = 7·6 in.	● Blank diameter = 8·1 in.	● Blank diameter = 7·6 in.
× Blank diameter = 8·0 in.	× Blank diameter = 7·7 in.	× Blank diameter = 8·2 in.	× Blank diameter = 7·7 in.



EFFECT OF LUBRICATION ON THE DISTRIBUTION OF THICKNESS STRAINS IN HEMISPHERICAL-HEADED STEEL CUPS

(e) *Full lubrication*	(f) *No lubrication*	(g) *Die-side lubrication*	(h) *Punch-side lubrication*
● Blank diameter = 8·5 in.	● Blank diameter = 8·3 in.	● Blank diameter = 8·9 in.	● Blank diameter = 8·1 in.
× Blank diameter = 8·6 in.	× Blank diameter = 8·4 in.	× Blank diameter = 9·0 in.	× Blank diameter = 8·2 in.

FIG 8

IRONING OF THIN-WALLED METAL CUPS

Some Effects of Lubrication on the Distribution of the Punch Load

In deep drawing, a blank of sheet metal is caused to assume some predetermined shape by subjecting it to a high load between a punch and a die in a press. When the radial clearance between the punch and the die is greater than the blank thickness, as in so-called

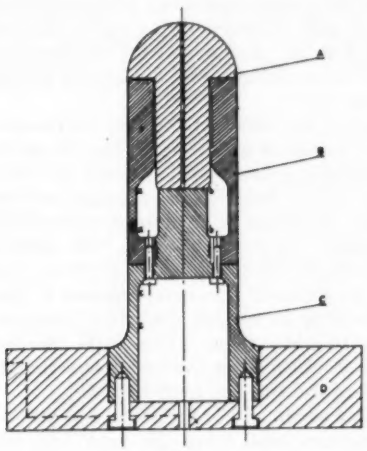


FIG 9
CROSS-SECTION OF IRONING PUNCH

"free drawing," there is theoretically no tractional force transmitted by the punch wall.

In an ironing operation, however, the radial clearance between punch and die is made less than the blank thickness, thus inducing a tractional force which is transmitted through the cup walls, which are thinned and lengthened during the process. By suitable choice of radial clearance, any desired degree of wall thinning may be achieved, the maximum reduction being limited by ultimate fracture in the cup walls. An ironing operation gives greater uniformity of wall thickness and improved surface finish to a drawn cup and, in industrial practice, is usually combined with drawing proper, such as in the manufacture of metal tubes.

Due probably to its somewhat limited industrial scope, there has been little research into the process of pure ironing, such as is involved when a previously drawn metal cup is ironed on a cylindrical punch. Research of this nature has, however, been in progress for some time at Sheffield University,[5, 6, 7] and a recent subject of investigation has been to examine the changes in the distribution of the load on the ironing punch when alterations are made in the following factors :

(i) reduction in cup wall thickness;
(ii) die angle;
(iii) lubrication.

Some of the effects of varying the conditions of lubrication are discussed in this paper.

The total load on the ironing punch can be conveniently split into two components, namely, the direct load on the punch head ("punch-head load") and the tractional load transmitted to the punch through the cup walls ("tractional load"). From a practical point of view, it is apparent that the relative magnitudes of these two components play an important part in the ironing process, since the punch-head load is a measure of the tension in the cup walls and, therefore, a prime factor in determining the maximum reduction which can be obtained with a given punch load. Further, since present theories of ironing assign specific characteristics to the separate constituents of the punch load, it is of interest to examine them experimentally, singly, and in combination.

With this aim in view a special composite ironing punch 4 inches in diameter was designed with a separate hemispherical head. A sectional view of the punch is shown in Fig 9. As can be seen, the punch consists of four distinct parts : the head *A*, the top wall *B*, the lower wall *C*, and the base *D*. Parts *B*, *C*, and *D* are rigidly bolted together, whilst the head *A* is a loose clearance fit inside the upper wall. Strain gauges mounted symmetrically round the inner face *a*,*a* of part *B* record the frictional load. To enable the punch-head load to be recorded, the head itself rests on the central spigot of part *C*, which has strain gauges mounted on its face *b*,*b*. As a check on the above sets of gauges and to record the total load directly, a third set is mounted on the inner face *c*,*c* of part *C*. Associated electronic equipment, which includes calibration devices and a punch travel indicator, enables autographic load diagrams on a basis of punch

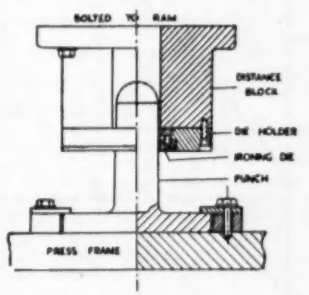


FIG 10
IRONING TOOLS

displacement to be photographed during an ironing operation.[8]

Experimental work was carried out on a 50-ton Cowlishaw–Walker experimental crank press at a speed of 8·3 strokes per minute. In practice, the ironing punch was rigidly mounted on the press table and the ironing die was bolted on the ram as shown in Fig 10.

All the test cups were first drawn on the ironing punch from circular blanks of nominal thickness 0·039 inch; the mild steel cups were afterwards bright normalized and the aluminium cups annealed. By the use of a set of dies of varying throat diameter, a range of ironing reduction, *i.e.* reduction in cup wall thickness, from 5 to 40 per cent was made possible.

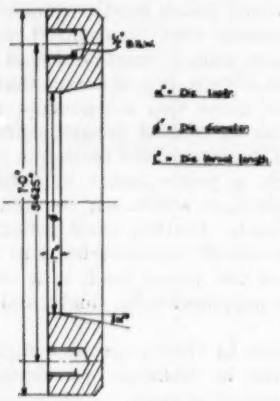


FIG 11

CROSS-SECTION THROUGH IRONING DIE

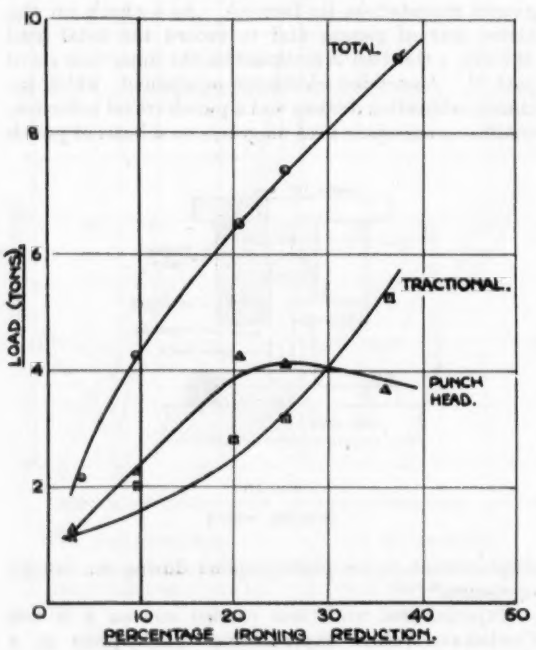
A cross-sectional view of a typical ironing die is shown in Fig 11.

Rather than carry out a complete series of tests with a wide range of lubricants, it was decided to experiment with only two types, a graphite and tallow mixture (1 part to 3 parts by weight) and a straight mineral oil. These two lubricants were considered representative of the best and worst types of drawing lubricant.

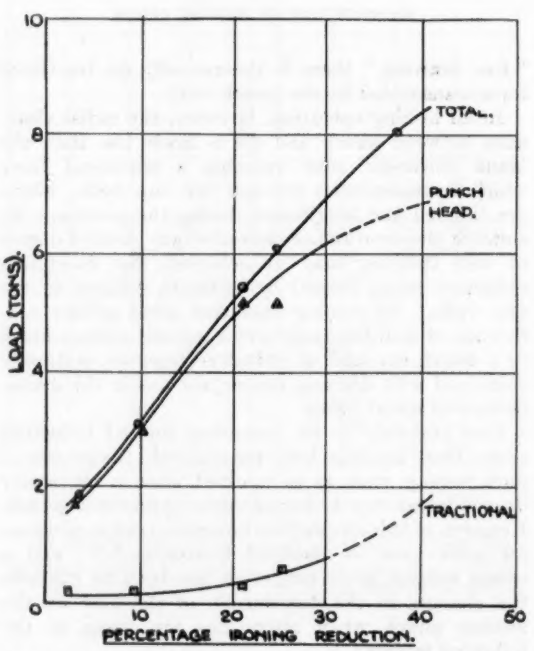
A comparison of the load-reduction characteristics for ironed mild steel cups when lubricated firstly with mineral oil and secondly with graphite and tallow is shown in Fig 12. The cups were lubricated on both inner and outer surfaces, and the ironing die taper was 10° in each case.

Comparing the effect of the two lubricants on the load constituents, it will be noted that whilst the total load is slightly greater with mineral oil, the punch-head load is considerably less, especially at the higher reductions, implying a significant reduction in cup wall tension. In point of fact, with graphite and tallow it was found impossible to perform a sufficient number of successful ironing operations at the 40 per cent reduction to enable the characteristics to be extended to this value. The cups, in this case, tended to fracture some distance down the cup walls after part of the cup had been ironed.

A further series of ironing tests was performed on soft aluminium cups using the same two lubricants



Die angle = 10°. Mineral oil lubrication on inner and outer surfaces.



Die angle = 10°. Graphite and tallow lubrication on inner and outer cup surfaces.

FIG 12

EFFECT OF DIFFERENT LUBRICANTS ON THE LOAD-IRONING REDUCTION RELATIONSHIPS FOR MILD STEEL CUPS

but varying the method of application in the following manner :

(1) inner surface of cup only lubricated;
(2) outer surface of cup only lubricated;
(3) both inner and outer cup surfaces lubricated.

In these tests all the cups were ironed to 30 per cent reduction with a 10° taper die.

It was found that, under the conditions of ironing chosen, all tests attempted with no lubricant between die and outer surface of the cup resulted in fracture of the cup wall approximately $\frac{3}{4}$ inch after ironing had commenced. Results for the remaining tests are shown in Table II.

TABLE II

Lubricant	Method of application	Total load, tons	Punch-head load, tons	Tractional load, tons
Graphite and tallow	Outside cup surface only	2·02	1·15	0·87
	Both cup surfaces	1·70	1·35	0·40
Mineral oil	Outside cup surface only	2·76	1·45	1·28
	Both cup surfaces	2·40	1·02	1·43

From a comparison of the ironing load and its two constituents under the different conditions of lubrication, the following points emerge :

(*a*) With both lubricants, the effect of lubricating the outer cup surface only was to make the total punch load greater than when both cup surfaces were lubricated.

(*b*) With mineral oil, the total load for both methods of lubrication is higher than that of the corresponding test with graphite and tallow.

(*c*) With graphite and tallow, optimum ironing conditions are obtained with the lubricant on the outside cup surface only.

(*d*) With mineral oil, optimum ironing conditions are obtained with the lubricant on both inner and outer cup surfaces. This result was somewhat unexpected, since it implies that with an aluminium cup interposition of mineral oil between the punch and inner cup surface worsens the conditions of lubrication.

To summarize the results of the various ironing tests, it can be stated that for optimum conditions of ironing it is desirable to employ a good drawing lubricant between the die and cup but to avoid good lubrication between punch and inner cup surface. Such conditions lower the total ironing load and, at the same time, reduce the tension in the cup wall, making possible a larger ironing reduction for a given punch load. This conclusion is anticipated by the ironing theory due to Sachs [9] and Swift,[5, 6] which predicts that any increase in the coefficient of friction between cup and punch wall will effect a reduction in the punch-head load without a significant change in the total ironing load; the theory also predicts that with given frictional conditions between punch and cup, reduction of total ironing load is achieved by decreasing the coefficient of friction between die and outer cup surface.

ACKNOWLEDGMENTS

The authors wish to thank the British Iron and Steel Research Association for permission to publish this paper.

Acknowledgment is due to Professor H. W. Swift for his continued interest and kindly advice in the course of the work. Also to Messrs. P. B. Mellor, P. Essam, and H. Leeming, who, as research students, undertook most of the experimental work described in the sections on the effect of punch form and lubrication in deep drawing operations and the ironing of thin-walled metal cups.

Special thanks are also due to the British Aluminium Co. Ltd., to Messrs. John Summers and Co. Ltd., and to Messrs. Richard Thomas and Baldwin Ltd., who kindly supplied the materials necessary for the experimental programmes.

References

[1] Swift, H. W. *Proc. Instn Auto. Engrs*, 1940, **34**, 361 and *Trans. Instn Engrs Shipb. Scot.*, 1943, **86**, 195.
[2] Loxley, E. M. "An Anomaly in the Drawing of Sheet Metal." B.I.S.R.A. Research Report No. MW/E/46/52.
[3] Swift, H. W. *J. Mech. Phys. Sol.*, 1952, **1**, 1.
[4] Chung, S. Y., and Swift, H. W. *Inst. Mech. Engrs War Emgcy Proc.*, 1952, **68**, 1.
[5] Lowe, R. N. F., and Swift, H. W. "Ironing of Mild Steel Cups." I.A.E. Research Report No. 1945/R/3.
[6] Knowles, W. S., and Swift, H. W. "Ironing of Metal Cups." I.A.E. Research Report No. 1946/R/3.
[7] Freeman, P., and Leeming, H. "Ironing of Thin Walled Metal Cups—The Distribution of the Punch Load." B.I.S.R.A. Report No. MW/E/46/53.
[8] Leeming, H., and Freeman, P. "An Autographic Recorder for Drawing and Ironing Loads." B.I.S.R.A. Research Report No. MW/E/58/51.
[9] Sachs, G., Lubarn, J. D., and Tracey, D. P. *Trans. A.S.M.E.*, 1944, **66**, A199.
[10] Mellor, P. B., and Loxley, E. M. "The Hydrostatic Bulging of Circular Metal Diaphragms." B.I.S.R.A. Research Report No. MW/E/36/52.

STUDY OF LUBRICATION IN WIRE DRAWING BY AN ELECTRICAL METHOD*

By A. E. RANGER and J. G. WISTREICH†

INTRODUCTION

LUBRICATION in wire drawing has, of late, become the subject of intensive research and development work, mainly as the result of difficulties encountered when attempting to draw much faster than has hitherto been the practice. It is now common experience when stepping up the drawing speed, that dies need to be replaced so frequently, as the result of more rapid wear, that the increased manning of machines and the cost of idle machine time more than offsets the gain in output expected from faster drawing. Thus the most important problem of lubrication in wire drawing at the moment is one of minimizing die wear. Since even in the most propitious circumstances die performance is variable, improvement of lubrication must ultimately be judged by the results of extended trials, analysed statistically. In research and development work, however, much expense would be saved and progress would be more rapid if the adequacy of lubricants could be judged by a test of shorter duration. Unfortunately, owing to the complexity of the phenomena involved and the imperfect understanding of them, it is not possible to rely on simulative tests; indeed, it is necessary to draw wire under conditions approximating to those experienced in practice.

The search for a criterion other than a die performance statistic has led to the study of the electrical resistance of the die–wire interface, for it seemed that the rate of die wear must be related to the extent of intimate contact between wire and die and to the frequency of its occurrence, and that this should be reflected by the magnitude and variation of the electrical resistance across the die–wire interface. It was reckoned that if wire and die,‡ which are both good electrical conductors, are separated by a continuous and fairly thick film of a lubricant which is an indifferent conductor, the resistance of the die–wire interface should be fairly high; a substantial drop in this resistance would then be indicative of local breakdown of lubrication, resulting in rapid die wear.

The idea of gauging lubrication by measurement of the electrical resistance across sliding surfaces, is not new. The method has been used in the study of cylinder, gear, and journal lubrication.[1, 2, 3] However, in those instances much thicker films of lubricant are involved than is probably the case in wire drawing. Thus, the technique had to be adapted to the circumstances and, owing to ignorance about the regime of lubrication prevalent in wire drawing, the validity of the foregoing tentative interpretation had first to be tested.

The investigation has, so far, centered on the "dry" drawing of bright mild steel wire about 0·1 inch diameter. Exploratory work was done at low speeds by industrial standards, but sufficient has already been done at high speeds, and in conditions approximating to those prevalent in industry, to warrant confidence in the method. The findings here recounted throw light on the question of the regime of lubrication in wire drawing.

METHOD OF MEASUREMENT AND INTERPRETATION

It has been common experience in the aforementioned investigations of lubrication that the resistance varies between "infinity" and "zero." It has been suggested [4] that the sudden drops in resistance are caused by local dielectric breakdown in the lubricant film. In the present experiments, however,

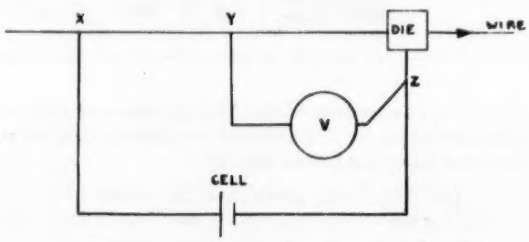


FIG 1
BASIC CIRCUIT

the possibility of breakdown was minimized, since the circuit included a fixed resistance in series with the film, which was large compared with the film resistance, so that the current through the latter remained sensibly constant. Moreover, the rapid oscillations of the resistance seen on the oscillograph traces here reproduced occurred over the whole range of current densities employed in preliminary experiments. This range was from 0·01 amp to 10 amp/sq. in. Assuming the order of magnitude of film thickness deduced from the experiment described below, this leads to electric stresses in the range 20 millivolts/mil (0·001 inch) to 20 volts/mil.

The basic circuit employed in this investigation is shown in Fig 1. Since the current in the circuit remains approximately constant, a measurement of potential difference between the points Y and Z gives an approximately linear measurement of the resistance between these two points.

* MS received 23 December 1953.
† Respectively, Investigator and Head of Metal Working Laboratory, British Iron and Steel Research Association.
‡ Only cemented carbide dies are considered.

The difficulty of making electrical contact with the moving wire was overcome as follows : In preliminary experiments on a low speed experimental machine the connexions X and Y were made to the drawing block, for it was found that the contact resistance between block and wire was negligible and the resistance of the length of wire between die and block was small and constant, so that the readings could be corrected for it. In subsequent experiments on an industrial machine and on a high speed experimental machine the contact resistance between wire and block no longer was negligible, and therefore the connexions X and Y were separated, X being made to a preceding die and Y to the preceding block via a slip ring assembly.

A further complication arises from the heat generated in the process. The die–wire interface temperature may reach several hundred degrees Centigrade at high drawing speeds, and since the wire and die are made of dissimilar metals a thermo-electric force is generated in the circuit. However, in the present experiments the magnitude of the thermal e.m.f. was found to be negligible in comparison with the potential drop across the lubricant film.

In order to interpret resistance measurements, the area of the die–wire interface must obviously be taken into account. The measurement of this area presented no difficulty, however, as an instrument for plotting profiles of dies to the required degree of accuracy, the BISRA Profilometer,[5] was available.

Owing to the pronounced roughness of the wire surface (see Fig 3) the film is likely to vary in thickness. The depth of the pits shown in Fig 3 can be much greater than the thinnest parts of the lubricant film, which are the most important from the point of view of lubricant breakdown. However, it can be shown that the observed resistance is related not to the average film thickness, but is weighted in favour of the thinnest sections of the film.

Suppose the combined area of the pits over the die–wire interface is A_1 and the average depth d_1. Let the remaining area of the wire be A_2 and the film thickness over this section be d_2. Then assuming a constant resistivity ρ, the total film resistance will be approximately

$$R = \rho/(A_1/d_1) + (A_2/d_2)$$

$$= \frac{\rho d_2}{A_2\left(1 + \frac{A_1 d_2}{A_2 d_1}\right)}$$

Since A_2 is, on the average, four or five times as large as A_1, and d_1 is of the order of 10 times the value of d_2, a good approximation is

$$R = \rho d_2/A_2$$

If the deduced film thickness is t, then

$$t = \frac{(A_1 + A_2)}{\rho} R = \left(\frac{A_1 + A_2}{A_2}\right) d_2$$

By microscopic examination of the wire surface, average values of A_1 and A_2 can be estimated.

Another factor affecting the relationship between film thickness and resistance is the resistivity of the lubricant. It is known that substances generally classified as insulators conduct electricity far better when in the form of very thin films than would be supposed from their bulk properties. This variation of resistivity with thickness is a serious difficulty, and is the main reason why the result of the film thickness calculation below can only be regarded as an indication of the order of magnitude.

EXPERIMENTAL

Slow speed experiments were performed on a single-hole experimental machine which imparts a vertically downward motion to the wire and is capable of continuous variation of speed between 0 and 100 f.p.m. In these experiments the wire was degreased prior to drawing, dipped in a bath of molten synthetic wax, and cooled to solidify the lubricant. The wax was used in preference to conventional soap because of its higher electrical resistance ; the resistance of the soap at speeds below, say, 20 f.p.m. was too small to be conveniently studied with the cathode-ray oscilloscope.

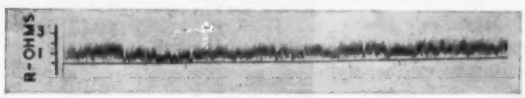


Fig 2

RAPID VARIATION OF RESISTANCE

(Film speed : 4 inches per sec)

(1) Initial experiments showed that, although the resistance was, on the average, in excess of one ohm, it was not steady but, on the contrary, varied rapidly with low values of about 10^{-1} ohms and peaks approaching on occasions 2 to 3 ohms (see Fig 2). In order to check whether "stick–slip" motion of the wire was responsible for this oscillation, a small electromagnet was attached to the wire between die and capstan, and the wire was made to pass through a fixed coil; the e.m.f. induced in the coil by the movement of the electromagnet was recorded with a cathode-ray oscilloscope. The arrangement proved sensitive to the slightest induced vibration of the wire. Yet, during drawing proper, there was no evidence whatever of jerky motion.

It is at first difficult to conceive of any other cause for this pronounced and rapid oscillation of resistance, seeing that dielectric breakdown is unlikely owing to the low level of the electric stress. The answer is probably to be found in the configuration of the wire surface. In spite of the high pressures prevailing in the die and of the mirror finish of the die, the surface of the wire is microscopically rough even when it has a bright and apparently smooth appearance (see Fig 3). Moreover, Figs 4 and 5 provide clear evidence that the wrinkles evident in Fig 3 are induced by plastic deformation in the die and change with it : Fig 4

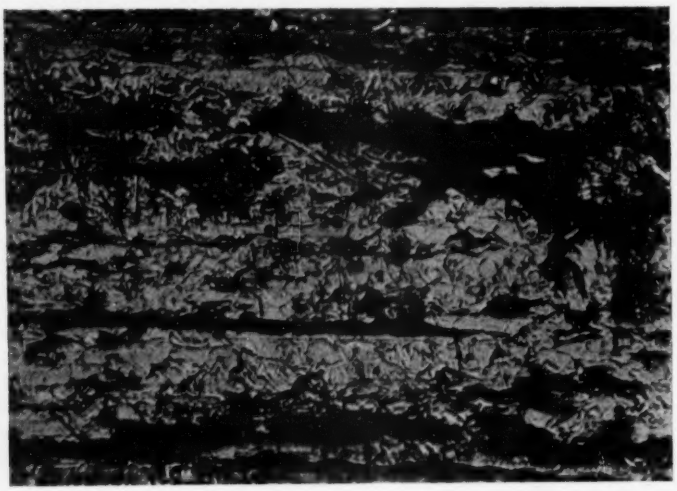


FIG 3
WIRE SURFACE SHOWING PITS (× 250)

FIG 4
WIRE SURFACE AFTER CENTRELESS GRINDING (× 250)

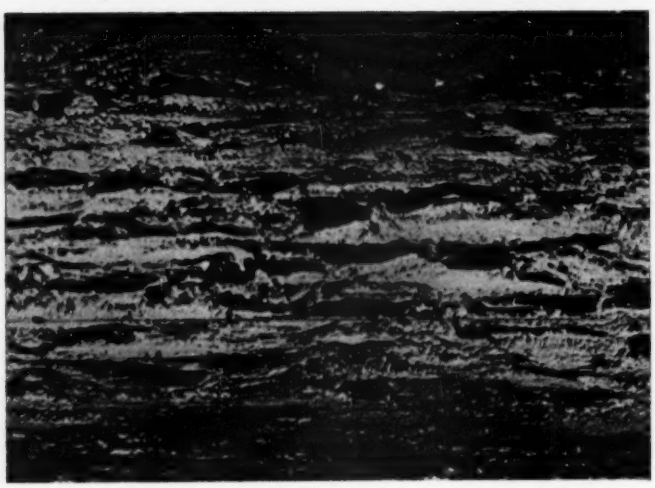


FIG 5
CENTRELESS GROUND WIRE SURFACE AFTER DRAWING ONE PASS (× 250)

shows the surface of a wire after centreless grinding, with circumferential grinding marks. Fig 5 shows the same wire after one pass.

(2) An attempt was next made to find to what extent a pronounced drop in resistance (to " zero ") could be associated with breakdown of lubrication. The wax coat was stripped from a 1-inch length of wire, and this area was degreased with trichlorethylene. The wire was then drawn at about 12 f.p.m., the bared portion being preceded and followed by appreciable lengths of wire well coated with wax. The cathode-ray oscilloscope trace recorded during this experiment is shown in Fig 6. It is seen that the resistance dropped suddenly to " zero " and remained there substantially for an interval approximately equal to the passage of the bared portion of the wire. It was also noted that in spite of the slight accumulation of surplus wax at the entry to the die, the drop in resistance practically coincided with the entry of the bared portion into the die.

|←Stripped length→|

Fig 6

EFFECT OF STRIPPING WAX FROM WIRE

(Film speed : 4 inches per sec)

It had been ascertained in earlier investigations that microscopic scratches usually appeared on wire if no lubricant was present. The onset of " zero " resistance preceded the appearance of a microscopic scratch (visible under a 250 × magnification), in an experiment in which the die temperature was raised progressively (see also Section 5). In another experiment, however, in which a narrow longitudinal scratch was made in the wax coat, no drop in resistance was recorded. In this case, apparently, the gap was filled in by surplus wax present on the wire.

(3) Whatever the speed, the resistance fluctuated rapidly, with the minima remaining fairly steady in magnitude. The peak values, however, increased with drawing speed, as evidenced in Fig 7. The effect of speed on mean resistance was studied by means of a heavily damped galvanometer; Fig 8 shows a

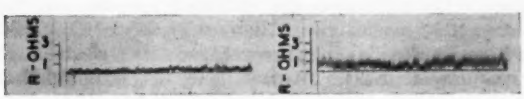


Fig 7

EFFECT OF INCREASE IN SPEED

(Film speed : 4 inches per sec)

typical record. It appears that at low speeds the average resistance increases linearly with speed (see Fig 9).

(4) In addition to being speed-dependent, the average resistance was also found to be markedly sensitive to the die angle. In two experiments per-

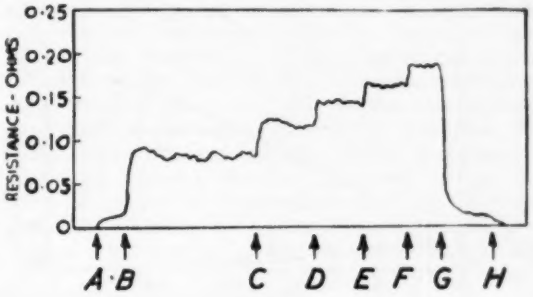


Fig 8

CHANGE OF RESISTANCE WITH SPEED

formed at 6 f.p.m. in which the die semi-angle, *i.e.* the wedge-angle between die and incoming wire was 1·9° and 5·3°, respectively, the resistances for unit area of contact were in the ratio 5·5 : 1. Since the mean die pressures in this case were approximately equal, one may conclude that it is a difference in film thickness which is largely responsible for the observed difference in resistance.

(5) Heating the die externally, so as to raise the temperature at the die–wire interface without changing the drawing speed, caused the film resistance to drop very markedly, as shown in Fig 10. Here

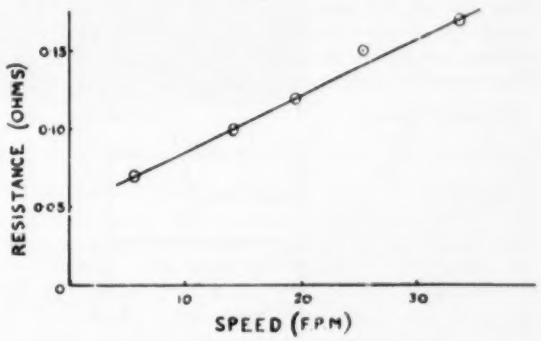


Fig 9

INCREASE OF RESISTANCE WITH SPEED

again the effect may confidently be interpreted in terms of change of film thickness rather than of resistivity owing to the rapid change of viscosity of the wax with temperature.

(6) An attempt was next made to determine the film thickness. Since a direct determination of resistivity of thin films of the lubricant under the very high pressures peculiar to wire drawing was impracticable, an experiment was devised in which ignorance of the resistivity is circumvented. Liberally precoated wire was drawn through two dies in succession, with

approximately the same reduction in each, the dies being about 3 inches apart, and the two average interface resistances were measured simultaneously by means of the circuit shown in Fig 11. Since not all the lubricant which passed through the first die

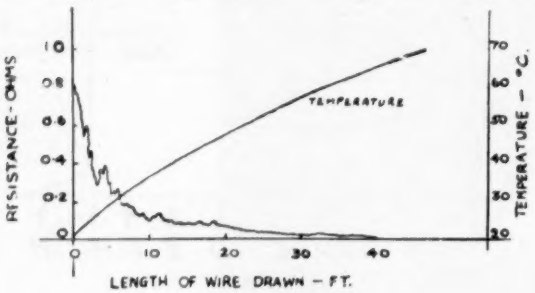


Fig 10

CHANGE OF RESISTANCE WITH TEMPERATURE

remained on the wire (some of it being stripped off by the second die), the difference in average film thickness between the two could be determined by weighing the stripped lubricant. A known length of wire was drawn, and the lubricant accumulated at the entry to the second die was removed and measured by dissolving in trichlorethylene vapour, filtering off contaminating matter (see below), and weighing the residue after evaporation of the filtrate. In the experiment in question the quantity of lubricant thus collected was 0·083 g for 53 ft of wire drawn, and this, allowing for size of wire between the dies (0·114 inches dia) and on the assumption of a uniform all-round reduction of film thickness, was equivalent to 7300 Å difference between the film in the first and second die. The measured difference in resistance per unit area of

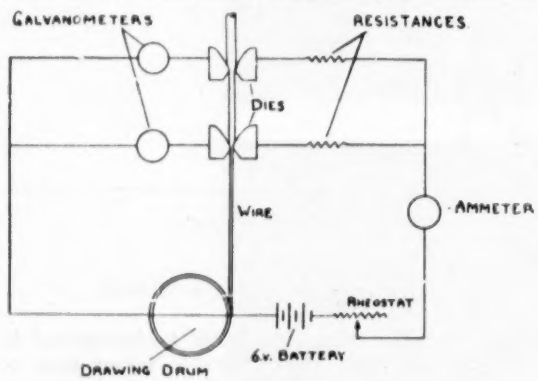


Fig 11

CIRCUITS FOR FILM THICKNESS DETERMINATION

die–wire interface was 0·0017 ohms/cm². If it is now assumed that the resistivity of the film in the two dies was approximately the same, then the average film thickness works out at 7900 Å in the first die and 600 Å in the second, with a resistivity of 150 ohm–cm.

It will be noted that the calculation involves the assumption of a constant film resistivity. The low value (150 ohm–cm) obtained would seem to indicate that this approximation is not valid, since the bulk resistivity is almost certainly greater than 10^{10} ohm–cm. The lubricant immediately adjacent to the wire, however, becomes contaminated with metal dust when deformation takes place, and it is considered that this is chiefly responsible for the low resistivity obtained. Further, it is assumed that the average resistance can be interpreted as an average film thickness. As the cause of the resistance oscillations is not fully understood, this procedure is, strictly speaking, unjustified; the point is more fully discussed in the final section. The assumption is also made that all the lubricant which passed through the first die remained on the wire. Some lubricant collected at the rear side of the first die, but the quantity was negligible in comparison with that accumulated at entry to the second die.

In order to check that only a top layer of the lubricant was removed, a microscopic examination of the

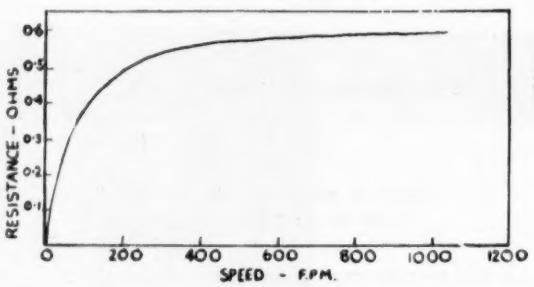


Fig 12

CHANGES OF RESISTANCE WITH SPEED

wire was made after drawing. It was found that the shape of the pits was consistent with the normal surface deformation and no closing, such as is experienced with insufficient lubrication, had occurred.

(7) Subsequent to the experiments so far described, further experiments were carried out on a high-speed, two-hole, experimental machine at speeds up to 5000 f.p.m. In this machine the wire is drawn horizontally and, at the moment, is lubricated in the conventional manner by passing through containers placed in front of the die and filled with soap powder. Bright drawn mild steel wire was also used. The average resistance at, say, 2000 f.p.m. was about 10 times that found in comparable experiments at 20 f.p.m. Even at high speeds the resistance still oscillated rapidly. At the same time, considerable changes in the general level of resistance lasting several seconds occurred at irregular intervals. In particular, it was noted that the resistance dropped to "zero" for fairly long intervals. If during such an interval the soap powder in the container was agitated, the "high" resistance immediately reappeared. It is known that the moving wire tends to wear a "tunnel" in the soap, so that temporarily it ceases to pick up sufficient soap; agitation presumably causes the "tunnel" to collapse and restores the desired pick-up. It has also been

noted that at first the resistance peak values markedly increase with speed, but above, say 500 f.p.m. there is little increase, if any, and the general level of the resistance peaks is much more unsteady than at low speed. The observed change is schematically shown in Fig 12. Moreover, at intermediate speeds the minima of the trace also tended to be markedly higher than either during slow or during very fast drawing. This effect, however, was intermittent, and did not occur consistently at or close to a particular speed. This observation accords well with the fact that at moderate speeds long slivers of soap emerge intermittently from the die, whereas at high speeds they give place to occasional " bursts " of slightly charred soap powder.

FIG 13

SURFACE OF WIRE STRETCHED IN TENSION (× 250)

DISCUSSION

Owing to the exploratory nature of the experiments here recounted, the interpretation of what has been observed is bound to be tentative in many respects. The findings do, however, unmistakably point to the conclusion that the regime of lubrication in wire drawing is intermediate between boundary and hydrodynamic. This view has been foreshadowed by Baron and Thompson,[6] who noted that the amount of soap passing through the die is greater at high speed than at very low speed. Kopczynski and Hoggart [7] have also arrived at this conclusion on the basis of the variation of the coefficient of friction with speed, inferred from interface temperature measurements.

Since, of all possible conditions of sliding, " thin film " (*viz.* " quasi hydrodynamic ") lubrication is least understood, the present investigation is of general interest. Blok [8] points out that in this regime the film thickness is a function not only of the " hydrodynamic " parameters—viscosity of lubricant, interface pressure and temperature, sliding speed, and wedge angle—but also of surface roughness and of the elastic and thermal properties of the sliding pair. The elastic modulus and surface finish of sintered carbide dies are usually so high compared with those of the wire that, to the first approximation, their influence on lubrication might be neglected. As against this, however, the present investigation has revealed two factors which greatly complicate matters.

In the first place, not only is the wire surface exceedingly rough on a microscopic scale, but its configuration changes markedly during the passage of the wire through the die. This may well be the principal reason for the oscillation of the interface resistance, which, it will be noted, was very rapid, not only at high drawing speeds but also when drawing very slowly. The phenomenon of surface wrinkling is not confined to wire drawing : Fig 13 is a photograph of the surface of a wire stretched in the tensile test; the surface was initially polished. Evidently the plastic deformation is exceedingly inhomogeneous on a microscopic scale, and presumably the changing surface configuration is an outward evidence of it.

Secondly, the contamination of the lubricant by metal particles was much greater than might be accounted for by wire and die wear arising from local intimate contact. Indeed, in many experiments here described the lubrication was exceptionally good by industrial standards, and no sign of scratching could be detected on the wire, even under high magnification. Moreover, judging by a magnetic test, the lubricant was contaminated right from the initiation of drawing. It is pertinent to note that, when stretched in a tensile testing machine, this wire became covered with a small quantity of metallic dust.

Although the calculation of the average film thickness here presented is to be regarded only as an

indication of the probable order of magnitude, it is supported by two other experiments. In the first the quantity of lubricant dropping off the wire as it emerges from the die, was measured in propitious conditions of industrial drawing. This quantity was equivalent to a 400 Å thick film over and above what remained on the wire. In another experiment carefully cleaned wire was coated with various measured amounts of soap by dipping it into solutions of soap in alcohol of various concentrations and drying before drawing. A " control " specimen without any lubricant seized in the die. It appeared from a comparison of drawing forces that in conventional lubrication the film thickness is in the order of 5000 Å or more (on the assumption of a smooth surface and uniform coverage). With all these approximate measurements as guide, one may estimate that the film thickness oscillates between, say, 1000 Å and 30,000 Å. These figures are well in excess of molecular dimensions of the lubricant.

One may infer from this that the coefficient of friction reflects friction within the lubricant rather than the work of breaking micro-welds between wire and die, which determines the rate of die wear. It is suggested that for this reason the coefficient of friction is not a suitable index of lubricant quality. Unfortunately neither is the electric resistance, owing to the dependence of resistivity on film thickness. However, for a particular lubricant, the interface resistance shows whether, currently, lubrication is good or bad. In this connexion, attention is drawn to the high-speed experiments in which the incidence of " tunnelling " could be observed, and therefore the efficacy of various remedies for it could be tested—and to the slow-speed experiment concerned with the effect of die angle, which suggests a method for finding the " optimum " die profile and for testing devices for thickening the lubricant film.

Note Added in Proof.—At Mr W. C. F. Hessenberg's suggestion Fig 10 has been replotted with the reciprocal of the absolute temperature as the abscissa, and the logarithm of the resistance as the ordinate. The equation $R \simeq 10^{-16}\exp(17{,}500/T)$ fits the data remarkably closely. This is analogous, in form, with Andrade's law for the temperature dependence of viscosity, suggesting that viscosity of the lubricant is the dominant factor in wire-drawing lubrication. Needless to say, this is merely an idea worthy of further attention and not a firm conclusion. In addition to the assumption about proportionality between film thickness and resistance, which has been discussed at full length in the paper, the above relation implies that: (1) the measured temperature was proportional to the interface temperature; (2) soap obeys Andrade's law at pressures prevalent in wire drawing.

References

1. Courtney-Pratt, J. S., and Tudor, G. K. *Proc. Instn mech. Engrs, Lond.*, 1946, **155**, 293.
2. Lane, T. B., and Hughes, J. R. *Brit. J. appl. Phys.*, 1952, **3**, 315.
3. Tudor, G. K. *C.S.I.R. (Australia) Tribophysics Division, Report A* 155, 1952; *J.C.S.I.R. (Australia)*, 1949, **21**, 202.
4. Courtney-Pratt, J. S., and Tudor, G. K. *Proc. Instn mech. Engrs, Lond.*, 1946, **155**, 293.
5. Withers, R. M. J. *J. Iron St. Inst.*, 1950, **164**, 63.
6. Baron, H. G., and Thompson, F. C. *J. Inst. Met.*, 1950, **78**, 415.
7. Kopczynski, S. Z. M., and Hoggart, J. S. *Aust. Engr*, April 1953, 73.
8. Blok, H. *Ann. N.Y. Acad. Sci.*, 1951, **53**, 779.

LUBRICATION OF STRIP IN COLD ROLLING MILLS*

By R. B. SIMS†

SUMMARY

The influence of friction on the force required to deform cold rolled material is described, and it is shown that changes in these frictional forces can cause appreciable variations in the gauge of the rolled product as the mill is accelerated and retarded. This off-gauge product can be serious, and this so-called " speed effect " has gathered importance in industry as rolling speeds have increased, and its control is now one of the major problems in the production of strip metal. An explanation is suggested for the speed effect which is supported by rolling experiments.

Notation and Units

R = radius of the undeformed work roll (inches).
H = entry thickness of the strip (inches).
h = exit thickness of the strip (inches).
M = elastic constant of the mill (tons/inch).
F = total load on mill (tons).
P = specific roll load (roll load per inch width of strip tons/inch).
k = yield stress of the material in plane compression (tons/in²).
Y = yield stress of material in uniaxial strain (tons/in²).
μ = coefficient of friction.

And, for any point on the arc of contact let:

y = strip thickness (inches).
p = pressure normal to the roll surface (tons/in²).
t = horizontal stress on strip (tons/in²).
θ = angular co-ordinate.

Stress is taken to be positive in compression.

INTRODUCTION

In the cold rolling process metal strip is passed between two hardened steel rolls which exert sufficient force on the material to deform it plastically. The strip is reduced in thickness and considerably elongated, but no substantial changes in width occur. Due to elongation of the material, the strip will leave the rolls faster than it enters, and, as the rolls rotate at a constant angular velocity, there is a difference between the peripheral speed of the rolls and the speed of the strip. In general, there is one plane in the arc of contact between the rolls and the strip where they move at the same velocity, and it is termed the neutral plane. Between the plane of entry of the

* MS received 4 November 1953. † Research Manager, Davy and United Engineering Company Ltd., Sheffield.

strip into the rolls and the neutral plane, the rolls are moving the faster, but between the neutral plane and the plane where the strip leaves the rolls, it is the strip which has the greater speed.

FRICTION IN THE COLD ROLLING PROCESS

The material is lubricated before rolling so that it slips over the roll surface, hence frictional forces are set up tangential to the rolls.

The forces which act on an element of the strip during cold rolling are shown in Fig 1. The point Q

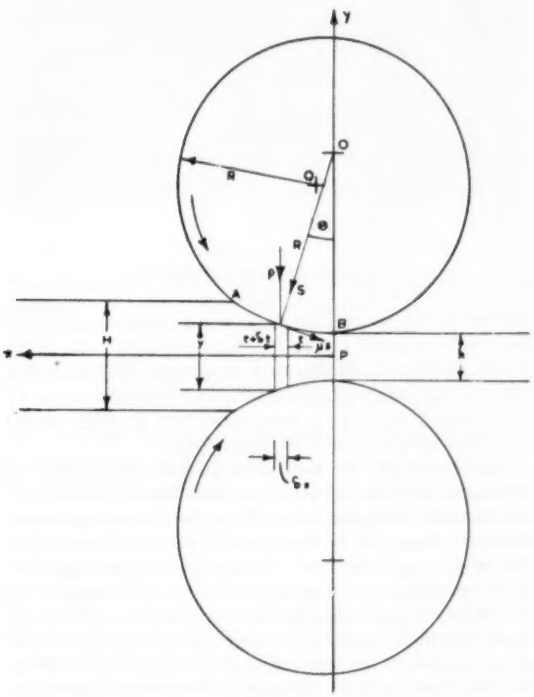


FIG 1

FORCES ACTING ON STRIP DURING COLD ROLLING

marks the centre of the rolls, but due to heavy forces exerted between the rolls and the strip, local elastic distortion takes place at the roll surface which greatly increases its radius of curvature. The frictional forces first act in the direction of motion of the strip, but at the neutral plane they are reversed and act in the opposite sense. The mathematical assumption that the frictional forces are reversed over a vanishingly small distance cannot be true in practice, but give model of the forces which is a sufficiently close approximation to the true distribution for calculations on rolling to be made with accuracy.

The frictional forces have a marked effect on the mill loading, since their effect is to increase the horizontal stress in the roll gap. The material will deform plastically under the applied stress distribution when the difference between the horizontal and vertical forces is equal to a function of its yield stress, and if the horizontal forces are increased by friction, therefore, a corresponding increase must occur in the vertical stress before plastic flow takes place. For most ductile materials the relationship between the horizontal and vertical stresses for plastic deformation in strip rolling is :

$$p - t = 2/\sqrt{3}Y = k \quad . \quad . \quad (1)$$

and the solution to the distribution of roll pressure may be obtained from it, together with the equation of equilibrium :

$$d/d\theta(ty) = 2R'(k + t) \tan(\theta \pm \mu) \cos\theta \quad . \quad (2)$$

There is no simple solution to this equation, and it is usually solved step-by-step. At the planes of entry and exit the pressure between the rolls and strip is equal to the yield stress of the material, and the horizontal forces are zero, unless external tensions are applied. Towards the neutral plane the pressure needed to deform the metal rises rapidly due to the increase in horizontal forces, contributed by friction, reaching a sharp peak at the neutral plane where the two equations implicit in equation (2) are satisfied simultaneously. When rolling thin sheet steel, the pressure between the rolls as the strip enters may be 45 to 50 tons/in^2, rising to over 200 tons/in^2 at the neutral plane. It should be added that the length of the arc of contact between the rolls and the material rarely exceeds 0·75 inch. The increase in rolling load due to friction may be seen in Table I, which

TABLE I

Effect of Friction on Specific Rolling Loads at Various Entry Thicknesses

Schedule no.	Entry thickness, H inches	Rolled thickness, h inches	Yield stress, k tons/in^2	Specific roll load, P_s		
				$\mu = 0{\cdot}05$ tons/inch	$\mu = 0{\cdot}08$ tons/inch	$\mu = 0{\cdot}12$ tons/inch
1	0·060	0·042	40	14·4	16·8	20·8
2	0·045	0·0315	40	13·7	17·2	21·5
3	0·030	0·0210	40	12·2	15·8	25·2

shows the calculated loads for deforming material at three different values of the coefficient of friction. They have been calculated for a mill with 10-inch-diameter work rolls for a reduction of 30 per cent in thickness without tension applied to the strip.

FRICTION AND CHANGES IN ROLLED STRIP THICKNESS

When a mill operator sets up his mill to roll a strip to given thickness, he sets the rolls apart by a distance S_0 which is smaller than the required thickness of the strip. In a great many instances the rolls are actually forced together under a heavy preload, so that S_0 has a negative value. On entering the strip a load is set up which compresses the rolls and stretches the mill frame. The distance between the rolls increases

because of this elastic distortion, and a very close approximation (Hessenberg and Sims [1]), the resulting gap is equal to the thickness of the rolled strip. Since the deformation is elastic, it will obey Hooke's law and :

$$F = M(h - S_0) \quad . \quad . \quad (3)$$

This equation provides the relationship between gauge and roll load. In a mill needed to roll tinplate, M may have a value of 10^4 tons/inch, and the maximum load on the mill may exceed 2000 tons. The effect of changes of roll force on the strip thickness and mill setting is considerable. When the maximum load is applied to a mill, the distance between the rolls may be increased by 0·200 inch due to elastic distortion, yet the strip leaving the rolls may have values between 0·030 and 0·009 inch, and must be rolled to close tolerances in gauge.

It has been shown above that the roll load depends on the coefficient of friction between the strip and the rolls. The equation to the load for a given plastic deformation of the strip may be written :

$$F = \psi(h) \quad . \quad . \quad . \quad (4)$$

where the function ψ is understood to include the effect of the pass reduction, friction, strip thickness, and width and the roll radius. The resultant value of the strip thickness may be calculated when equation (3), which is termed the elastic equation, and

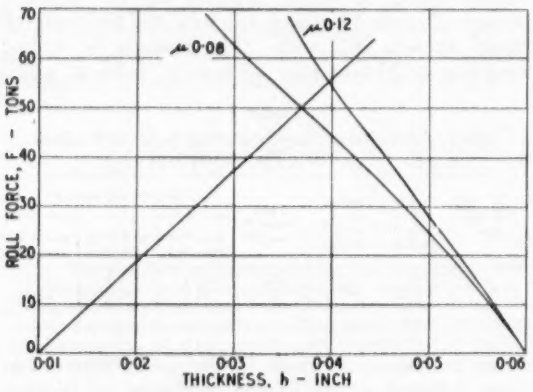


Fig 2

F/h DIAGRAMS OF 3- × 0·060-INCH ANNEALED STRIP

equation (4), the plastic equation, are solved simultaneously.

This solution may be carried out on an F/h diagram,[1] in which rolled strip thickness is plotted as abscissa and the total roll load F as ordinate. A solution is shown in Fig 2 for a piece of annealed steel strip, 3 inches wide and 0·060 inch thick, rolled with an initial setting on the rolls S_0 of 0·010 inch. The elastic equation is shown by the straight line (left) and the plastic equations for coefficients of friction of 0·08 and 0·12 by the curved lines on the right. The point of intersection gives the roll load and rolled strip thickness. When $\mu = 0{\cdot}08$, the strip thickness (h) is 0·0370 inch, and with $\mu = 0{\cdot}12$, h has the value 0·0397, an increase of 0·0027 inch, or 7 per cent of the final thickness of the strip. Changes of friction of this order during rolling are a characteristic of the process, and are discussed in detail below.

The Speed Effect in Rolling

Strip must be entered or " threaded " between the rolls at a slow speed, and when it is secured on the take up coil, the mill is accelerated to its normal production speed. A typical threading speed of a

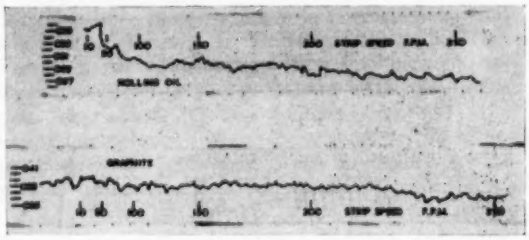


Fig 3

(*a*) OIL LUBRICATION
(*b*) GRAPHITE LUBRICATION

mill is 200 f.p.m., which is increased subsequently to 3000 or even 6000 f.p.m. It is found that as the mill is accelerated or decelerated, a change occurs in the rolled strip thickness. The effect is large. Changes of up to 0·010 inch have been observed in mills where the finishing gauge is 0·030 inch only.

The speed of the mill does not enter the rolling equations explicitly, hence an experiment was carried out to determine the speed dependent variable of the process. A survey of the possible causes showed that the effect could be due to a change in yield strength of the material, or a change in the elastic constants of the rolls or the coefficient of strip friction with speed. These variables were separated by rolling two halves of a single coil of steel of uniform initial thickness. One-half was rolled with an oil lubricant, the other was degreased carefully and coated with a suspension of colloidal graphite in alcohol, which was allowed to dry before rolling. The thickness of the strip was recorded as the mill was accelerated. The details of the experiment have been given by Sims and Arthur,[2] and the results are shown in Fig 3 (*a*) and (*b*). It will be seen from Fig 3 (*a*) that a change of thickness of 0·008 inch occurred on acceleration of the mill when rolling with an oil lubricant, but with graphite (Fig 3 (*b*)) only a small change took place in the strip thickness towards the end of the coil due to contamination with the oil from the mill bearings.

Talc and vermiculite were also used to suppress the speed effect of rolling; the latter lubricant, indeed, showing a small increase in strip friction with increasing mill speed. Clearly therefore the friction is the speed dependent variable of the rolling process.

The foregoing experiments were carried out with

rolls of an average roughness of 20 micro-inches measured axially. An opportunity occurred to repeat a few experiments subsequently after the rolls had been reground to a surface finish of less than 4 micro-inches. Copper strips 0·037 inch thick and 3 inches wide were rolled and lubricated with rolling oil. The results are given in Table II. It will be

TABLE II

Effect of Roll Surface Finish on Coefficient of Strip Friction

Entry thickness H, inches	Roll surface, micro-inches	Mill speed U, f.p.m.	Exit thickness h, inches	Coefficient of friction
0·0377	4 (Mirror finish)	8	0·0268	0·056
0·0368		53	0·0257	0·052
0·0376		98	0·0256	0·042
0·0369		203	0·0250	0·040
0·0374		294	0·0252	0·039
0·0371	22 (Matt finish)	8	0·0242	0·080
0·0370		28	0·0238	0·076
0·0371		51	0·0231	0·067
0·0372		101	0·0226	0·064
0·0365		150	0·0219	0·054
0·0371		202	0·0220	0·054
0·0369		245	0·0216	0·051
0·0372		296	0·0217	0·048

seen that the speed effect is nearly halved when rolling with mirror finished rolls.

THE MECHANISM OF THE CHANGE OF FRICTION WITH MILL SPEED

The Possible Variables Influencing Friction in Rolling

In their detailed investigation into the speed effect, Sims and Arthur [2] discussed three possible causes for the observed change in the coefficient of friction with mill speed: these were temperature, pressure, and rubbing speed. The work of rolling appears almost entirely as heat in the strip, and the temperature of the strip as it leaves the mill may be over 100° C. No correlation was found between the measured coefficient of friction and the energy liberated in the material, and hence its temperature after rolling. Additionally, Bowden and Tabor [3] have stated that, in general, the coefficient of friction does not change continuously with temperature, but a sudden change occurs when the melting point of the lubricant film is reached. No such abrupt changes in gauge were observed, and the coefficient of friction decreased uniformly with mill speed from 0·08 to 0·04, as shown in Table II.

In a similar way, there was no significant correlation between gauge changes and the roll pressure, and it was concluded by elimination, that the changes in gauge were due to changes in the rubbing speed between rolls and strip, although it was realized at the time that the relative speed was a function of the reduction in thickness, and the correlation between reduction and friction at any fixed mill speed was not significant.

Previous experimental work has shown that there is little or no variation in the coefficient of rubbing friction with speed. Thus Bowden and Tabor [3] measured μ for many combinations of metals and lubricants over the range 0·001 cm/sec to 2 cm/sec; Wells [4] carried out experiments at rubbing speeds up to 400 cm/sec; and Sampson, Morgan, Muskat, and Reed [5] covered the range 0 to 50 cm/sec. All these investigations found less than ± 5 per cent change in μ with speed over the range they covered.

The values of the measured coefficient of friction reported in the literature on friction agree well with the values found in rolling at low speeds. The only record of a change in friction on the magnitude occurring in rolling during acceleration is that found by Claypoole and reported by Karelitz,[6] and the change was not due to an increase in speed, but an increase in the number of layers of lubricant molecules deposited on the rubbing surfaces. Claypoole observed a decrease in μ from 0·10 to 0·04 when the number of layers increased from 1 to 20.

The suggestion has been made in the past that lubricant is drawn into the roll gap as the mill speed is increased to give hydrodynamic lubrication. This explanation is unlikely; first, because it is difficult to visualize an oil film supporting pressures met in the area of contact between rolls and material, which approximates to a fitted bearing of only 1° to 5° of arc, and secondly, as Ford [7] has shown, the speed effect in rolling occurs when the strip is rolled without an excess of lubricant.

A Suggested Mechanism of the Speed Effect

It is known that organic compounds containing a polar bond will form surface layers with reactive metals, which then function as a boundary lubricant. Examination of this film has shown that the first molecular layer is a metallic salt strongly oriented with the polar bond attached to the substrate, whilst the layers are less strongly oriented, and are finally deposited randomly.

Rolling lubricants all contain free fatty acids. Palm oil, which is used almost exclusively for tinplate rolling, may contain up to 14 per cent free acid. This is applied to the clean strip immediately after pickling, forming a layer of metallic salt and perhaps crystals of free acid. The work of Claypoole suggests a connexion between mill speed and the resulting coefficient of friction. When the strip enters the rolls at low speeds the solid deposit of lubricant flows off the surface away from the roll gap under the heavy applied pressures, leaving only a few strongly oriented layers attached to the material to serve as a boundary lubricant. As the mill speed is increased, less extrusion of the viscous deposit of the solid lubricant takes place since it is a function of time, and an increasingly thick layer of lubricant is driven into the roll gap and reduces the frictional forces. On the basis of this hypothesis, the speed effect in rolling, and in many other metal-forming processes, is dependent on the viscosity of the solid layer deposited by the lubricant on the metal.

Experimental Investigation

A direct verification of this "extrusion effect" on the lubricant layer with speed is difficult. It is possible, however, to verify a corollary of the hypothesis. The full speed effect in rolling should be obtained when the material is left in contact with the lubricant for sufficient time for the surface layers to form and then rolled after carefully removing all surplus liquid; but a reduced speed effect should be obtained if the experiments are repeated after removal of some of the superincumbent layers of the solid lubricant. Ideally, this second set of experiments should be made with layers of controlled thickness,

TABLE III

Experiments to Suppress Speed Effect—Copper Strip 3 inches Wide, 0·019 inch Thick

No.	Treatment	Mill speed U, f.p.m.	Exit thickness h, inches
1	Lubricated, washed and dried	20	0·0155
2		50	0·0147
3		100	0·0141
4		150	0·0135
5		200	0·0133
6		250	0·0128
7		300	0·0129
8	Cleaned with benzene	20	0·0154
9		50	0·0148
10		100	0·0142
11		150	0·0140
12		200	0·0142
13		250	0·0141
14		300	0·0138
15	Cleaned with benzene and MgO	300	0·0163
16		250	0·0164
17		200	0·0156
18		150	0·0161
19		100	0·0161
20		50	0·0162
21		20	0·0161
22		300	0·0163
23		250	0·0155
24		200	0·0159
25		150	0·0163
26		100	0·0163
27		50	0·0163
28	Flood lubricant	20	0·0147
29		50	0·0141
30		100	0·0138
31		150	0·0136
32		200	0·0134
33		250	0·0130
34		300	0·0125
35		250	0·0128
36		200	0·0137

using a technique such as that due to Langmuir and Blodgett to deposit successive monolayers. Unfortunately this method could not be carried out on the large specimens needed for rolling, and on a massive piece of apparatus such as a rolling mill. The following approximate experiments were carried out therefore, which, although qualitative, demonstrate the dependence of the speed effect on oil film thickness.

An annealed coil of 3-inch-wide high conductivity copper was prepared by rolling down from 0·060 inch to 0·0195 $\pm$ 0·0005 inch, and from it were cut pieces each approximately 6 ft in length. Towards the end of each piece, two lines were scribed 10 inches apart. The length and width of the strip between these reference lines were measured before and after rolling, and the strip thickness was measured after rolling by cutting six specimens 1 $\times$ 1 inch diagonally across the reference length and inserting them between the anvils of an electrical contact strip micrometer.

After preparation, all the strips were immersed together for 1 hr in a trough of a 10 per cent emulsion

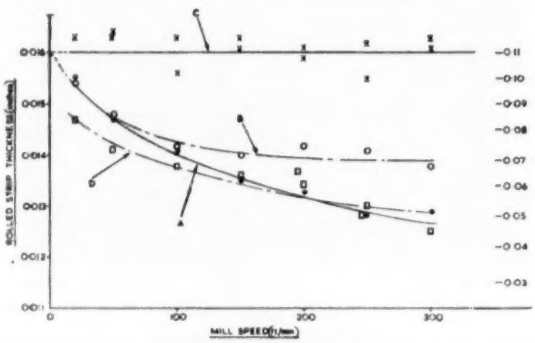


FIG 4

SUPPRESSION OF SPEED EFFECT ON 3 $\times$ 0·019-INCH COPPER STRIP

A—Strip rolled with solid lubricant, *B*—Strip cleaned in benzene, *C*—Strip cleaned in benzene + MgO, and *D*—Strip rolled flood lubricant.

of soluble oil in water. The rolls of the 10 $\times$ 10-inch two-high experimental mill was then adjusted, and the roll setting left undisturbed throughout the experiments. Changes of friction would then be indicated as changes in rolled strip thickness. The first seven pieces (1–7) were rinsed in water and dried off prior to rolling. The rolls and the parts of the mill near them were then carefully wiped down with swabs soaked in benzene, and then the rolls were thoroughly degreased with swabs carrying a water suspension of magnesium oxide.

The next set of seven specimens (8–14) were cleaned with benzene and rolled. After each one had passed through the mill, the rolls were cleaned with MgO. Specimens 15–27 were degreased with benzene and then lightly swabbed with a suspension of MgO in water. The lubricant layer was not completely removed by this treatment, since a deposit was removed from the rolls after each piece had passed through the mill, and a check was made on each piece for the presence of a surface layer by thorough cleaning with MgO, when coefficients of friction greater than 0·3 were obtained. The final set of nine specimens (28–36) were rolled immediately after removal from the bath of lubricant and with a flood of soluble oil coolant on the rolls. The results are given in Table III and Fig 4. It will be seen that with dried strips carrying a solid thick layer of lubricant (1–7) a large

speed effect has been obtained which does not differ greatly from that obtained when rolling with a flood of soluble oil coolant (28–36). Degreasing with benzene reduces the speed effect (8–14), particularly at the highest speeds, and the removal of all but the last few molecular layers suppresses the speed effect completely (15–27).

CONCLUSIONS

There is reasonable evidence in support of the hypothesis that the change in coefficient of friction with speed observed in rolling and also in many other industrial processes is due to a change in the thickness of a solid lubricant film deposited on the strip from the liquid.

In rolling, at least, there are methods available for controlling the speed effect. Systems of automatic gauge control have been described by Sims, Place, and Briggs.[8] Unfortunately, strip becomes more difficult to roll as it becomes thinner, and also the control of gauge becomes more difficult, the servomechanism becoming markedly slow in its response. In the extreme case, when rolling tinplate in large tandem mills, strip cannot be rolled to gauge at low speeds unless excessive tension is applied to the strip. It must also be remembered that the rolled product must be saleable and must be produced with a uniform finish of high lustre which is greatly dependent on the lubricant. These difficulties may be met and overcome by the provision of lubricants which are designed specifically with the rolling process in mind, and is a task requiring urgent attention from the petroleum chemist.

ACKNOWLEDGMENTS

The author is grateful for the help given to him by his colleagues K. H. Slack and W. Bagshaw, and to the Director of the British Iron and Steel Research Association for the use of the experimental rolling mill.

References

1. Hessenberg, W. C. F., and Sims, R. B. *Proc. Instn mech. Engrs, Lond.*, 1952, **163**, 75.
2. Sims, R. B., and Arthur, D. F. *J. Iron St. Inst.*, 1952, **172**, 285.
3. Bowden, F. P., and Tabor, D. "The Friction and Lubrication of Solids." London: Oxford University Press, p. 196.
4. Wells, J. H. *Engineer, Lond.*, 1929, **147**, 454.
5. Sampson, J. B., Morgan, F., Reed, D. W., and Muskat, J. *J. appl. Phys.*, 1943, **14**, 689.
6. Karelitz, G. B. *M.I.T. Conference*, 1940. Friction and Surface Finish, p. 102.
7. Ford, H. *J. Iron St. Inst.*, 1948, **156**, 380.
8. Sims, R. B., Place, J. A., and Briggs, P. R. A. *J. Iron St. Inst.*, 1953, **173**, 343.

LUBRICANTS FOR TUBE AND BAR DRAWING*

By A. L. H. PERRY† (Associate Fellow)

SUMMARY

The paper begins with a brief description of the various tube drawing processes. Then the requirements in a tube drawing lubricant are defined, the state of lubrication in tube drawing is discussed, and the lubricants encountered in practice are tabulated. Lubricant practice in the three main fields—steel, copper, and aluminium tubes—is then outlined, various existing problems being indicated. Finally, reference is made to the allied subject of bright bar drawing.

TUBE DRAWING PROCESSES

SEAMLESS tubes, both ferrous and non-ferrous, are initially produced by a hot working process, such as piercing, extrusion, or hot drawing, and the resulting hollows are the raw material for subsequent cold drawing operations. The hot worked hollows necessarily have somewhat inaccurate dimensions, and may vary considerably in circularity, wall thickness, and concentricity of the bore. They are also of rough surface and soft. Cold drawing converts these hollows into tubes of smaller section, accurate in form and dimensions, with good surface finish and of increased hardness. The increase in hardness can if desired be entirely or partially removed by annealing, and this permits the production of tubing with a range of physical properties, appropriate to different applications. The range of tubes handled by cold drawing extends from extremely fine tubing, such as that used for hypodermic syringes, up to large pipes.

Most cold drawing is carried out on straight-pull drawbenches, in which the tube is reduced in diameter by being pulled through a die in one of three ways—sinking, plug drawing, or mandrel drawing. In each case one end of the tube is first reduced by hammering, swaging, or push-pointing, so that it can be pushed through the die and gripped on the other side. It is then drawn through the die by a carriage, itself pulled by a heavy continuous chain, driven through gearing by a powerful electric motor.

In sinking, the tube has no internal support, and is simply pulled through the drawing die. Thus the bore size of the tube is not controlled, and sinking is therefore generally suitable only when the bore has neither to be within close tolerances nor to be particularly smooth. Sinking is also used for very small

* MS received 18 December 1953.

† The Shell Petroleum Company Limited.

tubing, such as that used for hypodermic needles, where to give inside support is normally not practicable. In sinking, both the outside diameter and the bore become smaller, and the wall thickness and length usually both increase a little. The absence of internal support limits the pressure exerted on the die, and hence sinking is a comparatively mild operation, being much less onerous than plug and mandrel drawing. Reductions in outside diameter (not thickness) in a sinking pass are normally about 20 to 25 per cent.

In plug or fixed mandrel drawing, the outside diameter of the tube is reduced by drawing through a die, on the inlet side of which, inside the tube, is a short cylindrical plug over which the tube is drawn. The plug remains on the inlet side of the die, being prevented from passing through it by attachment to a long rod or tube of smaller diameter secured at its rear end. The tube is reduced in wall thickness as it is drawn between plug and die. The plug controls the size and finish of the bore, and the die that of the outer diameter. Reductions of area per pass are normally about 30 to 40 per cent. Plug drawing is not generally used for tubes below about 0·25 inch diameter, because it then becomes impracticable owing to the small size of rod involved.

In mandrel drawing, internal support is given by a long ground steel mandrel, whose length is greater than that of the drawn tube. The tube is slid over the mandrel, so that both tube and mandrel are pulled through the die together. The tube wall is thus thinned down between the die and the mandrel, which is normally ground to a slight taper to facilitate removing the drawn tube. This is done, either by direct stripping-off in a stripping die, or by reeling, which loosens the tube and permits easy withdrawal of the mandrel. Because the mandrel moves with the tube, their relative motion is less than that of the tube and the stationary plug in plug drawing. Internal friction is therefore much less severe in mandrel drawing, and the attainable reductions are consequently greater, 50 per cent and over being reached. Mandrel drawing is therefore especially used for high reductions; also when large tubes are greatly reduced in outside diameter. Other uses are for tubes of too low a diameter for plug drawing, and for thin-walled tubes which would rupture with plug drawing. Otherwise, plug drawing is the preferred method, as plugs are much cheaper and less troublesome to maintain than long mandrels, which are expensive and easily damaged. Other determining factors are that it is not practicable to use mandrel drawing beyond a certain diameter, because of the high cost and weight of the mandrels, and that in mandrel drawing there is the extra job of removing the tube. The outcome of all this is that plug drawing is more widely used than mandrel drawing, while sinking is of minor importance only. In producing particular sizes and classes of tube, combinations of the three processes are often used. For instance, a final sink may be given after initial mandrel or plug draws.

The traditional straight-pull drawbench draws at speeds usually ranging between 30 and 60 f.p.m., though speeds as low as 10 and as high as 120 f.p.m. are also used. Provision is frequently made for drawing at more than one speed; and to avoid snatch loads at the outset, low-speed starting gear is also often fitted. One tube only is drawn at a time, and manual handling is the rule. Though expensive in labour, this type of bench is very flexible and can deal with a varied production programme.

In the semi-automatic type of bench the carriage is automatically returned to the front end of the bench after the draw by a counterweight and cord release, an arrangement that economizes in labour and is particularly useful when considerable numbers of one size of tube are to be drawn. As a further advance, in recent years completely automatic drawbenches have been introduced for the high-speed production of tubes with minimum manual handling. One type of automatic bench can draw up to three 25-ft tubes at a time, at speeds up to 200 f.p.m.; special benches draw lengths up to 100 ft at speeds up to 300 f.p.m. Designs vary, but the following is a typical process:

> The tubes are automatically fed from a loading rack, by chain-and-screw conveyors and pinch rolls, over the plugs and rods. They are then pushed hydraulically for a few inches through the die to point them in readiness for the actual draw (automatic push-pointing), and are afterwards plug drawn at any desired speed up to 200 f.p.m., steplessly variable drawing speeds being provided. Meanwhile another set of tubes is being prepared automatically for the draw. Drawing lubricant is circulated to dies and plugs by high pressure pumps.

The use of straight drawbenches limits the attainable length of tube, and the need for long lengths of certain types of tubing, particularly of copper tubing for domestic purposes, has consequently led to the development of the floating plug process. In this the plug is very short (about 1 inch long) and coiled tube is drawn round a rotating bull block as in heavy wire drawing. The plug is stepped in contour and automatically sets itself in relation to the die. Drawing speeds of 1000 f.p.m. and more are employed.

Until recent years, tube drawing dies and plugs were generally of hardened steel, sometimes chromium plated, but are now increasingly of the tungsten carbide type. The great hardness and resistance to wear of carbide justify its greater cost, particularly for producing large quantities of one size of tube.

LUBRICANTS FOR TUBE DRAWING

The most important requirement in tube drawing lubricants is that they should permit high reductions per pass while preventing pick-up between the tube and the die, plug, or mandrel. They should give long die life and also a good finish to the tube, though this point is not always so important as it is, for example, with wire and with rolled strip, because

tubes can be, and often are, polished after drawing. Similarly, cooling, which is an essential in lubricants for certain operations, is often unimportant in tube drawing, where the brevity and intermittency of the operation automatically prevent the development of undesirably high temperatures. This is usually not true, however, of the modern automatic benches. If these are to be used to the best advantage, circulating lubricants, giving some measure of cooling, are necessary.

The residual lubricant on the tube should not give staining in subsequent bright annealing, where this is used; but again, cleaning of the tubes prior to annealing is feasible and often done, though this is naturally avoided where possible. As a whole, therefore, with tube drawing lubricants the emphasis on purely lubricating factors is higher than with other chipless forming operations. It is therefore understandable that the outstanding problems in this category are connected with lubrication itself, rather than with auxiliary aspects such as staining.

As with other chipless forming processes, what the exact state of lubrication is in tube drawing cannot be said to be completely established. The high pressures involved preclude the possibility of fluid lubrication in the ordinary sense, but though boundary lubrication is the characteristic state, certain phenomena suggest the co-existence of some quasi-hydrodynamic condition. For example, the operation is often sensitive to viscosity, which is not true of pure boundary lubrication. Moreover, though E.P. agents are sometimes used in tube drawing lubricants, there appears to be little or no unimpeachable evidence of their value in this operation, though they may possibly be so in marginal cases. These considerations are reflected in the lubricants actually used, the most important being soap solutions, emulsions, and mineral or compounded oils.

The following classes of lubricant are encountered in tube drawing practice: dry soap powder, soap solutions, drawing compounds (with and without fillers), soluble oils, mineral oils, compounded oils, E.P. oils, mineral oils plus polymers, soft metal coatings (lead, copper, tin, zinc), "evaporative" lubricants (involving volatile solvents), graphite, bitumen, and waxes.

Sometimes more than one of the above lubricants is used in a particular operation. Tubes, particularly ferrous, are also often given pre-coating treatments, of which the main examples are as follows: iron oxide rust, lime, zinc phosphate, and iron oxalate. The application of these various lubricants and pre-coats for steel, copper, and aluminium tubes will now be discussed.

LUBRICANTS FOR STEEL TUBES—CARBON AND ALLOY STEELS

The hot-produced steel hollows that are the raw material for cold drawing are covered with scale, which must be removed before drawing. This is usually done in sulphuric acid, about 5 to 10 per cent concentration, heated in vats or boshes to about 70° to 80° C. The pickled steel tube is then water-washed and, in the old methods of handling, is allowed to rust, or dipped in a slaked lime bath, or in a soda bath, or in dry lime—there are various procedures, depending on the steel and the type of draw.

For the actual lubrication of the tube, the pre-dip method is generally used. In this method the tubes are immersed, usually for a few minutes only, in a tank of aqueous-base drawing lubricant, preferably heated to about 60° to 80° C. They are then removed and allowed to dry, which leaves a coating of lubricant both on the outside and on the bore. Sometimes drying is done in special dryers with forced draught. The lubricant is usually either a soap solution, or an emulsion of a drawing compound, containing from 5 to 20 per cent of soap or compound according to circumstances. The drawing compounds are mixtures of fat, soap, fatty acid, and water, sometimes with mineral oil also present. The concentration and temperature of the bath determine the thickness of the lubricant coating, which in turn influences the severity of the draw that can be taken. To help the lubricant to remain on the metal during drawing, the tube is often allowed to rust after pickling and before immersion in the lubricant. As a rule one pass only is given; the tube is then annealed, pickled, and drawn again; and the cycle repeated as often as required. In some cases, however, the tube is given more than one pass, with the one lubricant coating, before annealing. Sometimes, *e.g.* with high carbon steels, dry powdered lime is applied to the tube after the pre-dip application of lubricant, and serves as a cushioning agent to protect the die. For difficult work, drawing compounds loaded with a filler are often used, common fillers being talc, chalk, and mica. After pre-dipping, the filler remains on the tube along with the soap, fat, etc., and serves as a solid cushion that helps to prevent pick-up and scoring. A typical content of filler in the original compound is 20 to 30 per cent.

The virtues of the pre-dip method are that the resulting film of lubricant will withstand more severe drawing conditions than solutions or emulsions of the same lubricant, owing to the concentration effected by the removal of water during drying. Moreover, the one process provides lubricant for both bore and outside surface.

Special pre-coating treatments are also widely used in steel tube drawing to reduce die wear, eliminate pick-up, and permit heavier reductions. A former method was to dip the tube in a solution of copper sulphate, which gave a copper coating to the outside and to the bore. (Zinc and cadmium coatings applied by electroplating have also been used to some extent.) However, these processes have now largely given way to the use of coatings of phosphate, likewise applied after pickling and before immersion in the dip tank. The phosphate undercoat in itself serves as an anti-welding layer, and also acts as a carrier for the lubricant, which is less readily wiped off during drawing

than from a bare tube. Drawing with phosphate undercoats is now probably the commonest technique for carbon and alloy steels, an outstanding advantage being that tubes can be given several passes between anneals.

A given plant may handle a considerable variety of carbon and alloy steels, in different sizes, and this often leads to the use of several different combinations of pre-coats, lubricants, and drawing and annealing schedules.

LUBRICANTS FOR AUSTENITIC STAINLESS STEEL TUBES

The well-known propensity of austenitic steels to work harden rapidly makes the drawing of tubes in this material particularly difficult, and gives rise to special lubricant problems. For high reductions and die life the best of known lubricants is a coating of metallic lead. The hot-produced stainless steel hollow is thoroughly pickled in a mixture of nitric and hydrochloric or hydrofluoric acids, and after a dip in a flux, *e.g.* of zinc and mercuric chlorides, is then immersed in a bath or " bosh " of molten lead, where it receives an internal and external coating of this metal. It is then plug-drawn, sometimes with the lead coating only, sometimes with another lubricant also, such as a drawing compound emulsion. Several passes can then normally be taken before annealing is required, each pass giving about 20 per cent reduction of area. What is left of the lead is removed by immersing the tube in nitric acid.

Successful though it is, there are objections to the lead coating which prevent its universal adoption. Especially, it is expensive and troublesome to apply and remove. This is particularly so with large diameter tubes, for which the lead bath would need to be extremely large and expensive. Lead coatings are also avoided when the stainless tubes are to be used for food handling, owing to the toxicity hazard from unremoved lead. In these cases, alternative methods of lubrication are used. For example, with very large tubes that are only to be sunk, a mixture of powdered soap, graphite, and possibly also powdered lime may be applied to the pickled tube as it enters the die. For mandrel or plug drawing of smaller tubes, these may first be given a pre-dip treatment in a drawing compound emulsion or in a soap solution, allowed to dry, and drawn with the further application of a mixture of graphite and lime. Various modifications of such systems are used in different works.

Another class of lubricant involves the use of lithopone. Mixtures of lithopone and linseed oil, lithopone and soap, and mineral oil, lithopone, and shellac are all known to have been used, being applied by the hot pre-dip and dry method. Other lubricants incorporate bitumen: one such contains bitumen, fatty matter, and an E.P. additive, and is applied in a volatile solvent, which evaporates to leave a hard resistant film. Yet another type of lubricant is the chlorinated wax, used either in the neat form or cut back with mineral oil, and applied by swabbing or circulation. All these types perform well up to a point, but are unable to withstand conditions as severe as can the lead coating; they are therefore normally applied only with smaller tubes, and for mandrel rather than the more severe plug drawing.

These lubrication difficulties have led, as with carbon steels, to the use of pre-coating techniques. One such, now well established, uses a bath containing oxalic acid, which confers a layer of ferrous oxalate on the tube. The tube with its oxalate pre-coating is then drawn with an emulsion of a conventional drawing compound, usually containing a filler. As with phosphate coatings on carbon steel tubes, the oxalate coating improves die life and permits greater reductions and more passes between anneals.

LUBRICANTS FOR COPPER AND COPPER ALLOYS (BRASSES, BRONZES, CUPRONICKELS, ETC.)

Because of their lower tensile strength, the tube drawing of copper and its alloys is less severe than that of steel, and this is reflected in the lubricants used, the field as a whole being adequately served by conventional lubricants without recourse to either pre-coating or the use of special lubricants.

As with steel, the hot produced hollows are first pickled in sulphuric acid and washed and then drawn on non-automatic benches, conventional drawing compounds being widely used. Usually these are either swabbed in the neat condition on the tube and plug, or applied in emulsion form by the hot pre-dip method. For the harder alloys, such as bronze or cupronickel, compounds containing a filler are sometimes preferred. Alternatives are heavy oils such as cylinder oil, fatty oils such as tallow, and blends such as cylinder oil plus tallow.

Automatic benches are now coming into widespread use for copper and its alloys, usually drawing at speeds of 200 to 300 f.p.m. A pump-circulated lubricant, fed through a hollow tube to the plug, and sprayed over the tube as it enters the die, is required; it must be readily circulable and should not cause staining in the subsequent bright annealing, normally carried out in burnt towns gas. Compounded or E.P. mineral oils, with viscosities generally in the range 100 to 300 Redwood 1 at 140° F, are one type used (though whether E.P. properties are helpful in this application is controversial); another is a soap solution. Neither type so far satisfies all requirements perfectly. Chatter and even breakage, especially if the tubes are wet, are encountered with the oils; and the soap solution does not permit the use of the highest bench speeds.

As mentioned above, bull block drawing, using a floating plug of tungsten carbide, is now widely used for producing long lengths, up to several thousand feet, of copper tubing for domestic purposes. Drawing speeds up to 1200 f.p.m. are reached in this process, which is not a severe operation from the lubrication

aspect, light mineral or compounded oils, circulated and sprayed on the tube as it enters the die, being satisfactory. Adequate internal lubrication is provided by introducing a shot of the same oil inside the tube by means of an oil gun before drawing.

LUBRICANTS FOR ALUMINIUM AND ALUMINIUM ALLOY TUBES

Certain properties of aluminium lead to special features in drawing practice. The absence of scaling in hot working means that the hot worked hollows do not need pickling before drawing. As the metal is softer even than copper, and much softer than steel, it would be expected to be very mild in its wearing action on dies. However, the very hard surface oxide always present can lead to heavy die wear. Aluminium is also very prone to pluck and tear in working operations, an effect, Bowden suggests, that may be due to the unusually large difference in hardness between the oxide and the underlying metal, brittle fracture of the oxide being followed by tearing of the soft metal below. A notable feature of aluminium is its unusual susceptibility to the influence of lubricant viscosity, suggesting that quasi-hydrodynamic conditions obtain to an unusual extent, no doubt because of the softness of the metal. The higher the oil viscosity, the more severe the operation that can be performed, and as tube drawing is intrinsically a severe operation, high viscosity oils are generally necessary, and are the most common type of lubricant used. Both straight mineral and compounded oils are used, but though compounding may help to improve die life, it is probably a minor factor compared with viscosity. A usual range of viscosities is from about 50 to 250 Redwood 1 at 212° F, but for the most severe requirements, such as very large tubes, grades containing polymers, with viscosities such as 500 to 1000 Redwood 1 at 212° F, are used. Reductions per pass generally vary from about 25 to 40 per cent, according to circumstances. Unattractive aspects of the need to use high viscosity lubricants are that they are difficult or impossible to circulate, and unless removed by degreasing beforehand they cause staining at the low annealing temperatures used with aluminium. Apart from heavy oils, various other types of lubricant are used. In terms of reductions per pass, the most effective is what is sometimes called the evaporating type, which consists of a wax or soap base lubricant dissolved in a volatile solvent, usually trichlorethylene. The tubes are dipped in the lubricant and drained; the trichlorethylene is then allowed to evaporate, leaving a hard, strong, adherent coating, which gives reductions of the order of 40 to 50 per cent per pass and allows several passes to be made with one application of lubricant. After drawing is completed the coating of lubricant is dissolved away in trichlorethylene. Unfortunately, such lubricants have several incidental defects. The trichlorethylene is expensive, and precautions must be taken against its toxic fumes; the lubricant is rather troublesome both to apply and to remove; and the drawn tubes have a dull finish. Nevertheless, this type of lubricant holds a strong position in U.K. practice, essentially because of the high reductions obtained; this correspondingly reduces the number of passes, and speeds up production.

Another pre-dip method uses an emulsion of a soluble drawing oil. The tubes are dipped into, say, a 10 per cent emulsion of the oil, drained, and allowed to dry. The resulting coating of lubricant permits reductions of the order of 25 to 30 per cent, and several passes can be made with one coating.

None of the present lubricants for aluminium tube drawing is entirely satisfactory. What is needed, especially for automatic benches, is a lubricant giving reductions of the order of 50 per cent per pass; of low enough viscosity to be readily pump-circulated to both die and plug; and not needing removal before annealing. To meet all these requirements at the same time represents an outstandingly difficult problem.

BRIGHT BAR DRAWING

Bright bar drawing is done in the same type of benches as tube drawing, but, as there is no internal surface to be sized and lubricated, it is a much simpler process, and has hardly any special features. It therefore needs only brief reference here.

Hot-produced steel bars are first pickled, then dipped in lime, and finally baked. They are then drawn through steel or carbide dies, using either circulated lubricants (oils or emulsions of drawing compounds) or being passed through a box of dry soap powder, tallow, or neat drawing compound. Oils for circulation may be of the straight mineral, the compounded, or the E.P. variety; viscosity is probably the dominant property, and viscosities of the order of 100 to 150 Redwood 1 at 140° F are common. Drawing compounds are of the filled or unfilled varieties according to the severity of the work. Modifications of this general scheme, such as dispensing with baking of the lime, are also encountered.

Drawing of copper and copper alloy bars follows the same general lines as for steel, except that there is no liming, and that dry soap powder is never used as lubricant. Aluminium and its alloys are treated on different lines; as with tubes, the most usual lubricant is a heavy mineral or compounded oil, pump-circulated to the bar as it enters the die.

CONCLUSION

Ideally, metal working lubricants should be easy to apply, should cope in themselves with every lubricating requirement, and should afterwards be innocuous and thus not need to be removed. What tube drawers would like is low viscosity, readily volatilizable non-staining lubricants, with ample film strength to give high reductions per pass. The above survey shows how far existing tube drawing lubricants fail to

meet these requirements. Auxiliary treatments are common, application methods are often troublesome, and lubricants must often be removed if staining is to be avoided in the anneal. Fundamentally, these deficiencies arise out of the nature of tube drawing lubrication, which lying as it does in some ill-defined region between the boundary and the hydrodynamic, generally imposes solidity or high viscosity as inescapable lubricant properties; these in turn give rise to the other problems. However, the recent rapid extension of the use of automatic drawbenches has focused attention on these problems, and it is to be hoped that this will lead to the development of lubricants of greater efficiency for this exacting service.

ACKNOWLEDGMENT

The author wishes to thank the directors of The Shell Petroleum Co. Ltd. for permission to publish this paper.

TUBE-DRAWING OILS: THE FUNCTION OF FATTY AND E.P. ADDITIVES *

By J. S. McFARLANE and A. J. WILSON

INTRODUCTION

In tube-drawing the lubricant performs the triple function of reducing the friction, protecting the working surfaces from wear, and cooling the tools. It is clear that some part of the high loads between the forming tools and the tube may be borne by a fluid film promoted hydrodynamically, but it is certain that the lubricant is also called upon to provide boundary lubrication. This is shown by the facts that dies and plugs are subject to wear and to pick-up of the tube metal, both of which are typical boundary processes, that the viscosities of the lubricants used cover a wide range without directly affecting the draw-load, and that the coefficients of friction appear to be of the order of 0·03 to 0·1, *i.e.* much higher than the coefficients normally encountered under full fluid film conditions. On this basis there are three types of oil-based lubricant which merit attention: the plain mineral oil, the oil containing fat, and the oil with fatty and "extreme pressure" (E.P.) type additives. The intention in this work has been rather to determine the way in which these materials function as boundary lubricants than to pursue the relative merits of the many formulations within each class.

The diversity of factors that influence the mode of operation of the lubricant in tube drawing is such that complete confirmation of the behaviour of a lubricant can be obtained only by extensive drawbench trials in which tool wear, frequency of break-offs, and the propensity of the lubricant to form objectionable surface coatings on the tubes are closely observed. In this investigation, the results of draw-bench load measurements are regarded as the final criteria, but a boundary friction apparatus, in view of its obvious flexibility and convenience, has been employed to provide the bulk of the experimental data, and such important factors as the temperature, speed, and time factors in the application in use of the lubricant have thus been clarified. The die loads developed during the tube-drawing trials have been employed to confirm the applicability to drawbench conditions of the results of the boundary friction tests.

THE BOUNDARY FRICTION APPARATUS

Design of the Apparatus

The apparatus used to investigate the boundary lubricating properties of the tube-drawing oils is similar in principle to that described by Bowden and

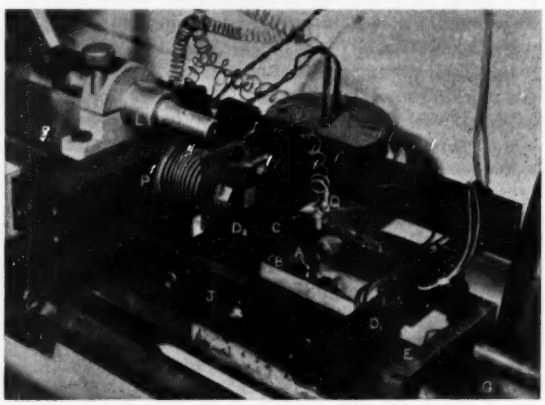


FIG 1

MEASURING HEAD OF THE BOUNDARY FRICTION APPARATUS

Leben,[1] though different in detail. The friction measuring head of the apparatus is shown in Fig 1.

The two surfaces between which the friction is measured are labelled *A* and *B*. *A* consists of a short hemispherical-ended ¼-inch diameter rod mounted on a bar *C*, which is connected to a frame *J* by the spring strips D_1, D_2. The frame *J* forms part

* MS received 10 November 1953.

of a lever system which can be used to apply any desired normal load between A and B, while strain gauges mounted on the spring D_1 are employed to measure the horizontal load between A and B, this measurement being obtained photographically from an oscillograph. The hydraulic damper P was inoperative during this investigation.

The flat horizontal surface B, on which the end of the rod A rests, consists of a $3 \times \frac{3}{4} \times \frac{3}{16}$-inch plate clamped to a sliding table E, which can be moved, by a hydraulic system, along the lathe bed G at any desired speed up to 1 cm/sec. The table E incorporates a hotplate for conducting tests at up to 200° C, the surface temperature of B being measured by a thermocouple Q.

As used for these experiments the spring suspension system had a spring constant of 8·5 kg wt/cm and a natural frequency of 25 c.p.s.

The geometry of the frictional contact (a sphere sliding on a flat), together with the high contact pressure and the low speed of sliding, ensure that the hydrodynamic pressure tending to lift the slider off the plate during sliding is negligibly small. Hence the normal and frictional forces are borne entirely by points of solid contact between the surfaces, and the coefficients of friction measured correspond to true boundary conditions of sliding.

The metal surfaces were prepared by abrasion against carborundum paper (grade 320) under a stream of distilled water, followed by drying in a blast of hot air. Surfaces prepared in this way may fairly be called clean and grease-free, though they are presumably covered by a thin oxide film and adsorbed layers of gases and water vapour.

A flame-cleaned glass rod was used to apply the lubricant to the surfaces.

Types of Sliding Encountered

As is now well known, the sliding of one surface over another may take place either smoothly or in a series of jerks. The type of sliding which takes place is determined by the nature of the surfaces and of the lubricant.

For the purposes of developing tube-drawing lubricants, however, measurements of the coefficient of friction during smooth sliding are of greatest importance, as these enable quantitative comparisons to be made between the lubricant performance on the drawbench and on the boundary friction apparatus. It is also of interest to consider the jerky sliding which occurs on some occasions on the boundary friction apparatus, to see whether this phenomenon is related to the chatter which can occur in tube-drawing.

When vibrations are engendered, they are often of the relaxation or saw-tooth type. The term "stick–slip" motion, used by Bowden and Leben,[1] is then very descriptive. The relative motion between the surfaces, instead of being smooth, appears to be made up of alternating periods of no relative velocity (during which the motion is taken up in the elasticity of the surfaces and their supports) and of rapid slip (during which the elastic energy is quickly dissipated as frictional heat). These alternating periods may be aptly termed the "stick" and the "slip."

Fig 2 shows three typical friction traces obtained on the boundary friction apparatus. The first is characteristic of smooth sliding, during which the displacement of the upper surface from its initial position (indicated by the dotted line) remains essentially constant. The second shows "stick–slip" sliding of small amplitude: here the upper surface attains a maximum deflection, then slips back rapidly, under

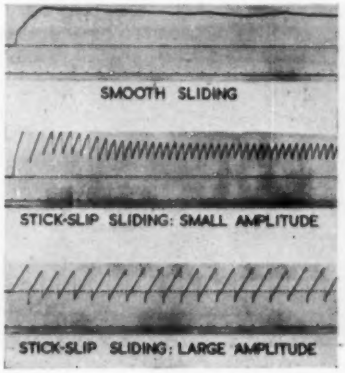


FIG 2
THREE TYPICAL FRICTION TRACES

the elastic forces in the suspension system, to a point still well above the zero line, is then picked up again by the lower surface at the beginning of the next slip, and so continues indefinitely to execute relaxation oscillations. The third trace is similar, except that the amplitude of the "slip" is much greater and the upper surface flies back beyond its initial position before being again picked up by the lower surface as it moves steadily onward.

It is evident that, though the size and mechanical constants of the boundary friction apparatus are greatly different from those of a tube-drawing bench, there is nevertheless a fundamental similarity between the conditions obtaining in the two operations. Thus both involve the steady motion of one component (specimen B or the tube respectively) past another component which is elastically restrained (specimen A on its spring beams, the plug on its plug rod, or the die in its holder).

With this in mind, it is interesting to compare the friction traces of Fig 2 with the vibrations shown in Fig 3. This figure shows the load variations which occurred in the plug rod of the experimental drawbench when the plug was chattering. The irregular rising lines indicate the "stick" condition when the plug moved with the tube, while the "slip" condition was too fast to be recorded. The rapidity of the sliding and accompanying load decrease has, however, excited numerous vibrations in the plug rod which have persisted during the subsequent "stick" period, causing the observed irregularities in the recorded trace.

Judging from the similarity of these phenomena, it may be said that when a lubricant gives rise to "stick-slip" motion on the friction apparatus, it is liable to lead to plug chatter on the drawbench, whereas if the lubricant shows a flat friction–velocity characteristic and smooth sliding on the friction apparatus, then a smooth draw is ensured in practice.

However, it would be unwise to regard the boundary friction apparatus as a drawbench in miniature, for the speeds, mode of deformation of the metal, and rate of generation of frictional and other heat are all quite different. The justification for using the friction apparatus as a means of investigation is that it is much more convenient and cheaper to use than a drawbench and that it permits a more analytical study of the lubricants to be made.

FIG 3

RECORD OF THE PLUG LOAD VARIATIONS ACCOMPANYING PLUG CHATTER

BEHAVIOUR OF VARIOUS OILS ON THE BOUNDARY FRICTION APPARATUS

Oils Used

Low friction and smooth sliding, combined with the ability to minimize pick-up on the tool surfaces, are the primary requirements for a tube-drawing oil at all likely operating temperatures. These factors are interrelated, for Rabinowicz and Tabor [2] have shown that pick-up increases very rapidly for quite small increases in friction, while die ringing, attributed by Wistreich [3] to high stress concentrations at the point of entry of the tube into the die, is likely to be minimized when the friction is low.

Friction tests have therefore been conducted on four types of oil to ascertain the relative merits of each type and thus avoid the uncertainties associated with hit-or-miss testing of proprietary brands of lubricant.

The series of oils used in this investigation was as follows:

Oil A: A plain mineral oil (extracted from a naphthenic base; viscosity at 100° F = 44·3 cs; V.I. = 66).

Oil B: A mineral oil with fatty additive (naphthenic oil of 198 cs viscosity at 100° F containing 3 per cent oleic acid).

Oil C: A mineral oil with fatty and mild E.P. agents (65 per cent naphthenic oil, 20 per cent mildly sulphurized fat, 10 per cent chlorinated heavy hydrocarbons, 5 per cent lead soap).

Oil D: A mineral oil with fatty and active E.P. agents (80 per cent naphthenic oil, 20 per cent highly sulphurized fat of a reactive nature).

Choice of Metal Surfaces

To simulate the drawbench conditions as closely as possible, tungsten carbide or chromium plate as the upper friction specimen and a series of other metals (say copper, brass, cupro-nickel, etc) as the lower would have been used. Such a choice leads immediately to difficulties, however, as transfer of material from each friction specimen to the other takes place in the course of a friction run just as it does in tube-drawing. The rates of pick-up in the two cases are not necessarily the same, so that it would be impossible to say at what stage the upper specimen was in a condition precisely equivalent to that of a tube-drawing die or plug. To compare the oils fairly on the friction apparatus it is necessary to prepare the surfaces in a standard condition, but a means of preparing the hard surface of the slider with a standard amount of pick-up does not readily suggest itself.

For these reasons the oils were tested between identical pairs of several different metals, *e.g.* copper on copper, a practice that was found to reveal differences in lubricant behaviour to a much greater extent than tests between dissimilar metal pairs. (The reason for this is not understood.)

Results for Copper Sliding on Copper

Table I shows the coefficients of friction obtained at five different temperatures and under two conditions of test designated "Long Exposure" and "Short Exposure." The speed of sliding was 0·08 cm/sec, and the normal load between the surfaces was 2 kg wt. The coefficients of friction are given to the nearest 0·05. A rather large number of repeat tests would be required to obtain frictional coefficients to a greater accuracy than this.

The values given under the heading "Long Exposure" are those obtained when the oil is applied to the whole of both metal surfaces at the outset of the experiment and the measurements then made successively at each level of temperature. The metal surfaces are thus exposed to the oil throughout the experiment, which may occupy 15 to 20 minutes.

Considering this set of results, we see that the plain mineral oil is a poor lubricant even at room temperature, and that it rapidly deteriorates as the temperature is raised; "stick–slip" sliding occurs throughout. Mineral oils of greater viscosity than oil A have also been tested, but these also were very poor boundary lubricants.

Oil B, containing 3 per cent oleic acid, gives substantially better behaviour: smooth sliding and low

friction are maintained to 100° C, though beyond that temperature the friction rises markedly and " stick–slip " motion ensues.

There is nothing to choose between the behaviour of oils C and D. The presence of E.P. additives is revealed by the maintenance of low friction and smooth sliding even at the highest temperatures.

Preliminary trials with oil C on a full-size automatic drawbench showed that the performance was not so good as would be expected from the laboratory experiments under " long exposure " conditions. Plug chatter occurred sporadically, and there were some tube break-offs. The disparity in performance seemed likely to be related to the different times available for the lubricant to act upon the metal under the two sets of conditions.

TABLE I

Coefficients of Friction for Copper Sliding on Copper with Various Lubricants, in the Temperature Range 20 to 180° C

Lubricant and type of additive	Long exposure					Short exposure				
	20° C	60° C	100° C	140° C	180° C	20° C	60° C	100° C	140° C	180° C
None	1·50 *	1·50 *	1·50 *	1·50 *	1·50 *	—	—	—	—	—
Oil A (none)	0·15 ‡	0·20 ‡	0·20 ‡	0·45 ‡	0·55 ‡	0·15 ‡	0·25 ‡	0·45 ‡	1·05 †	1·50 *
Oil B (fatty)	0·10 *	0·10 *	0·15 *	0·50 ‡	0·60 ‡	0·15 *	0·15 *	0·15 †	0·45 ‡	0·80 ‡
Oil C (fatty + mild E.P.)	0·15 *	0·15 *	0·15 *	0·10 *	0·05 *	0·15 *	0·15 *	0·20 †	0·35 ‡	0·20 ‡
Oil D (fatty + active E.P.)	0·15 *	0·15 *	0·15 *	0·10 *	0·05 *	0·15 *	0·15 *	0·10 *	0·10 †	0·05 *

* Smooth sliding. † Stick–slip sliding of small amplitude. ‡ Stick–slip sliding of large amplitude.

No information appeared to be available on this aspect of the function of E.P. additives; it is usually assumed that they react instantaneously when temperatures rise and seizure is imminent. Accordingly, the experimental procedure was modified to investigate the time factor. The oil, instead of being spread over the whole of the surfaces at the outset of each test, was applied as a small drop to the point of contact between the upper and lower friction specimens and held in position by surface tension forces. The pool thus made contact with each part of the lower specimen just before the upper specimen slid over it; the time available for the oil to form a lubricating film on the metal plate was very much reduced, and did not exceed 1 second. The results of these tests are shown in Table I under the heading " Short Exposure." Comparison of these results with those obtained by the earlier method reveals that :

(1) The plain mineral oil A behaves rather worse than under " long exposure " conditions.

(2) The other three oils are unaltered in behaviour at temperatures up to 100° C; the formation of the lubricating film appears to be virtually instantaneous.

(3) At temperatures above 100° C the behaviour of the oil appears to be critically dependent on the nature and reactivity of the additives present. Fatty additives alone (oil B) are ineffective, mild E.P. agents (oil C) are not as effective as under " long exposure " conditions, but highly reactive E.P. agents (oil D) give similar results with either method of testing.

Fig 4 illustrates the effect of the time of exposure on the damage caused to the flat copper surface during friction tests with oil C at 140° C. The upper track, which was produced under " long exposure " conditions, is seen to be smooth and uniform. The lower track, however, which was produced under " short exposure " conditions, shows much heavier surface damage, and is clearly marked with striations corresponding to the " stick–slip " motion.

Experiments with further test oils, containing chlorinated instead of sulphurized additives, showed that for copper surfaces such additives were not beneficial. The addition of 10 per cent of an active chlorine-containing agent to an oil already containing 10 per cent oleic acid and 10 per cent fish oil did not improve the lubrication. Under " short exposure " conditions at 140° C both oils gave a friction coefficient of about 0·4. Under " long exposure " conditions the chlorinated oil compared unfavourably with the unchlorinated fatty oil, the coefficients being 0·35 and 0·10 respectively. (The much lower friction of the

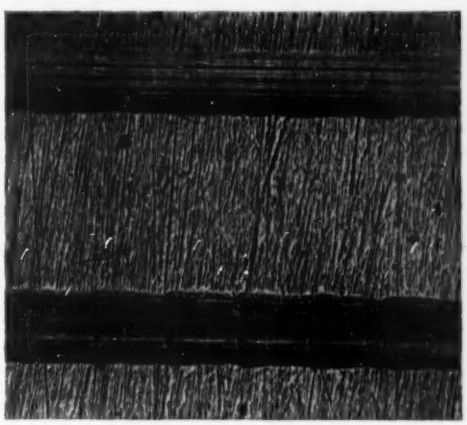


FIG 4

FRICTION TRACKS AT 140° C WITH OIL C. UPPER TRACK : LONG EXPOSURE. LOWER TRACK : SHORT EXPOSURE

latter oil compared with that given by oil B is due to its far greater fatty content.)

Where metals other than copper are present in the sliding system, chlorinated additives might show to better advantage, possibly owing to the different crystallographic natures of the chlorides that might then be formed.

Tests with Metals other than Copper

It was clearly of interest to find out how far the influences of lubricant composition and time of exposure, so important on copper, were effective on other metals and when a relatively inert material is used as the slider. Accordingly, tests with oils A, B, C, and D were made for " long exposure " and " short exposure " conditions using the following metal pairs :

(1) Brass on brass (65 per cent Cu, 35 per cent Zn).

(2) Cupro-nickel on cupro-nickel (75 per cent Cu, 25 per cent Ni).

(3) Aluminium–brass on aluminium–brass (76 per cent Cu, 2 per cent Al, 22 per cent Zn).

(4) Tungsten carbide on copper.

The results are shown in Table II. The salient features of the table may be summarized as follows :

(1) Brass behaves similarly to copper.

(2) Cupro-nickel resembles copper and brass in that the plain mineral oil A is not able to provide good lubrication on it. However, oil B, containing 3 per cent oleic acid, appears to be quite effective over the whole temperature range, and does not suffer the severe breakdown at high temperatures that is observed with copper and brass. With " short exposure " oil C gives results identical with those of oil B, while for " long exposure " the mild sulphurized additive appears to give some benefit at the highest temperatures. The active sulphurized additive of oil D is of some small further advantage under both sets of conditions. Unlike copper and brass, cupro-nickel gives smooth sliding under most conditions, although some stick–slips were observed with oil A at low temperatures and friction values.

(3) Aluminium–brass seems to be less demanding of the lubricant than the three metals so far discussed. Oil A is not an effective lubricant for it except at room temperature, but the coefficients of friction are not so high as those found with copper, brass, and cupro-nickel. The remaining oils behave very similarly to each other and, except under " long exposure " conditions, there seems nothing to be gained from the addition of the sulphurized E.P. agents, whether of mild or active nature. Even under " long exposure " conditions the gain is only small. Smooth sliding was observed throughout these tests.

TABLE II

Coefficients of Friction for Several Pairs of Metals with Various Lubricants, in the Temperature Range 20° to 180° C

Lubricant	Long exposure					Short exposure				
	20° C	60° C	100° C	140° C	180° C	20° C	60° C	100° C	140° C	180° C
Brass on brass										
None	0·55 ‡	0·65 ‡	0·75 ‡	0·90 ‡	0·90 ‡	—	—	—	—	—
Oil A	0·25 ‡	0·30 ‡	0·50 ‡	0·65 ‡	0·75 ‡	0·15 ‡	0·25 ‡	0·55 ‡	0·75 ‡	0·75 ‡
Oil B	0·10 *	0·10 *	0·30 ‡	0·50 ‡	0·50 ‡	0·10 *	0·10 *	0·40 ‡	0·55 ‡	0·55 ‡
Oil C	0·10 *	0·10 *	0·10 *	0·10 *	0·05 *	0·10 *	0·15 *	0·20 †	0·20 ‡	0·30 ‡
Oil D	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·15 †	0·15 †	0·10 *
Cupro-nickel on cupro-nickel										
None	1·50 *	1·55 *	1·55 *	1·60 *	1·60 *	—	—	—	—	—
Oil A	0·20 ‡	0·35 ‡	1·25 *	1·40 *	1·35 *	0·15 ‡	0·30 ‡	1·30 *	1·40 *	1·40 *
Oil B	0·10 *	0·15 *	0·15 *	0·20 *	0·15 *	0·10 *	0·15 *	0·15 *	0·15 *	0·15 *
Oil C	0·10 *	0·15 *	0·15 *	0·10 *	0·05 *	0·10 *	0·15 *	0·15 *	0·15 *	0·10 *
Oil D	0·10 *	0·10 *	0·15 *	0·10 *	0·05 *	0·10 *	0·15 *	0·15 *	0·15 *	0·05 *
Aluminium–brass on aluminium–brass										
None	1·25 *	1·25 *	1·30 *	1·30 *	1·30 *	—	—	—	—	—
Oil A	0·15 *	0·15 *	0·20 *	0·45 *	0·50 *	0·15 *	0·20 *	0·35 *	0·45 *	0·50 *
Oil B	0·10 *	0·10 *	0·20 *	0·20 *	0·20 *	0·10 *	0·10 *	0·15 *	0·20 *	0·25 *
Oil C	0·10 *	0·15 *	0·20 *	0·15 *	0·20 *	0·10 *	0·15 *	0·15 *	0·20 *	0·25 *
Oil D	0·10 *	0·15 *	0·20 *	0·15 *	0·10 *	0·10 *	0·15 *	0·20 *	0·20 *	0·20 *
Tungsten carbide on copper										
None	0·45 ‡	0·45 ‡	0·50 ‡	0·60 ‡	0·70 ‡	—	—	—	—	—
Oil A	0·10 *	0·10 *	0·10 *	0·10 *	0·20 ‡	0·10 *	0·10 *	0·10 *	0·10 *	0·15 ‡
Oil B	0·10 *	0·15 *	0·10 *	0·10 *	0·15 ‡	0·10 *	0·10 *	0·05 *	0·05 *	0·10 ‡
Oil C	0·10 *	0·15 *	0·15 *	0·10 *	0·05 *	0·10 *	0·10 *	0·15 *	0·10 *	0·10 *
Oil D	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·10 *	0·05 *	0·10 *

* Smooth sliding. † Stick–slip sliding of small amplitude. ‡ Stick–slip sliding of large amplitude.

(4) The combination of tungsten carbide on copper gives the lowest friction of all, and is also the least sensitive combination for discriminating between lubricants. These results, which refer to a tungsten carbide slider freshly cleaned for each test and therefore not subject to cumulative pick-up of copper at the point of contact, confirm the suitability of these two materials for operating together provided that pick-up of the copper can be avoided.

In short, it may be seen that with two of the metals (copper and brass) fatty additives are not effective over the whole range of temperature, and, if the temperature exceeds about 100° C and the time of contact with the oil is short, low friction can be obtained only if an active E.P. agent of the sulphurized type is added to the oil.

With the remaining combinations it is found that, though plain mineral oil is not a sufficiently effective lubricant in itself, the addition of a fatty additive (such as 3 per cent oleic acid) suffices to fortify the oil against the rigours of high temperature and short contact time.

The case of tungsten carbide on copper is peculiar in that, whereas an oil such as oil B gives poor results between two copper surfaces, it is nevertheless effective for tungsten carbide on copper, even though it can hardly be assumed that the tungsten carbide itself reacts with the oil to form a protective film.

The brief conclusion of these experiments is that with cupro-nickel and aluminium–brass a free fatty acid, such as oleic acid, is able to promote low friction at all temperatures up to 180° C, even though the time of contact be short. With copper and brass, however, the fatty acid is not effective above about 100° C, and a sulphurized E.P. additive is then essential if low friction is to be obtained. Furthermore, this additive needs to be of a reactive nature in order that it may react with the copper or brass to form the necessary protective film within the short time available to it in tube-drawing.

EXPERIMENTAL DRAWBENCH

The tube-drawing investigations were made on a 10-ton drawbench equipped with load-measuring equipment and provided with a gearbox to give several drawing speeds ranging from 12 to 220 f.p.m.

Plastic theory has not advanced to a stage which would enable the operative coefficient of friction definitely to be established from measurements of the drawing load. Nevertheless, as the load required to deform the tube should not be sensibly affected by the frictional load, differences in drawing load provide a direct measure of the frictional changes involved when using different lubricants.

Lubricants were tested on the drawbench by drawing a series of tubes of the same size and material through dies of progressively decreasing diameter until a limit was reached in the reduction which could be effected. The die loads for each test were recorded for comparison with the reduction in area effected.

All the tubes were plug drawn, the plug being mounted on a long plug bar, which provides a support having an appreciable degree of elastic freedom. When the lubrication of the plug is faulty, the plug is alternately dragged along with the tube and then springs back owing to the elastic restraint of the plug bar. Oscillations are thus set up. These are commonly called plug chatter, and may, in extreme circumstances, cause irregularities in the tube bore and circular markings on the outer surface of the tube. In all the trials here reported, observation of the plug bar for signs of chatter was continuously kept.

BEHAVIOUR OF VARIOUS OILS UNDER DRAWBENCH CONDITIONS

Oils Used

The four types of oil, designated A, B, C, and D, in the section on the " Behaviour of Various Oils on the Boundary Friction Apparatus," were used for drawing experiments.

Preparation of the Tube Surface

All the tubes were annealed before the tests, pickled in warm sulphuric acid, and subsequently washed in clean water. After draining and thorough air drying, the tubes were liberally swabbed with the oil to be tested immediately prior to their insertion in the drawing die. " Pointing " was effected before the annealing process to reduce the tube handling necessary between cleaning and lubricating, so that the risk of accidental contamination of the tube surface was reduced to a minimum.

There would undoubtedly be traces of oxide and minute quantities of deposited salts from the dried-off wash water present on the surface of tubes prepared in this way, but, although the surfaces were not as clean as those employed in the boundary friction tests, they were certainly grease-free. The tube surface presented a dull, slightly uneven or etched appearance, which would be very favourable to the performance of the lubricant.

Range of Tests

Annealed Oregon refined Canadian copper tubes were plug drawn on the experimental drawbench using tungsten carbide dies, in which the entry contour radius was equal to the die bore, of which the parallel portion was $\frac{1}{4}$ inch long, and the chromium plated plugs having a taper of 0·002 inch per inch. Drawing was effected at a speed of 12 f.p.m.

The tubes were all nominally 0·562 inch bore and 0·048 inch wall thickness before testing, and from this size each was reduced using plugs and dies chosen to effect approximately the same percentage reduction in wall thickness and tube outside diameter. Four plug and die combinations were employed, giving 10, 20,

30, and 40 per cent reduction of area respectively, at least two tubes being drawn through each die with each of the four lubricants that were tested. One tube from each of these conditions was measured before and after drawing to determine precisely the reduction in area which had been effected.

Die loads were measured by a mechanical load-meter, the calibration of which was found not to have varied during the period of the tests.

Results of Drawbench Tests

Details of the mean die loads measured during the tests are recorded in Table III, and Fig 5 shows all the experimental points. The contribution of friction to the die load is not large, and it is therefore unfortunately necessary to assess variations in coefficient of friction from small differences in relatively large quantities. The very small scatter between the loads measured on tests under similar conditions does, however, enable conclusions to be deduced with a fair degree of certainty.

It is evident in Fig 5 that no great demands are made upon the lubricant for small reductions of area, and, as the results for the four oils tested are indistinguishable at 10 per cent and 20 per cent reduction in area, that plain mineral oils afford adequate protection for the surface, and fatty and other additives are not required. Such is not, however, the case when the reduction exceeds 30 per cent. The plain mineral oil is inferior in performance here to the oils containing fatty and other additives. The decrease of some 10 per cent in die load in this region may possibly represent a factor of as much as 2 between the coefficients of friction of the fatted and non-fatted oil. A difference in performance between these two types of oil (samples A and B) is maintained up to the limiting reduction attempted.

A somewhat surprising effect is seen to occur when a relatively heavy reduction is effected when using samples C and D, for their performance is slightly but consistently poorer than that of the fatty oil containing no E.P. agents.

TABLE III

Die Draw Stresses when drawing Annealed Copper Tubes at 12 f.p.m.

Lubricant	Reduction of area %	Mean die draw stress, tons/sq. in. $\left(\frac{\text{die load}}{\text{final tube area}}\right)$
Oil A	8·8	2·7
	20·5	7·2
	33·5	12·2
	40·8	15·1
Oil B	8·2	2·5
	20·1	7·0
	32·9	11·0
	40·8	13·5
Oil C	8·1	2·5
	20·2	7·0
	32·8	11·0
	40·8	14·4
Oil D	20·5	7·1
	33·2	10·9
	40·8	14·4

No plug chatter was observed during these tests.

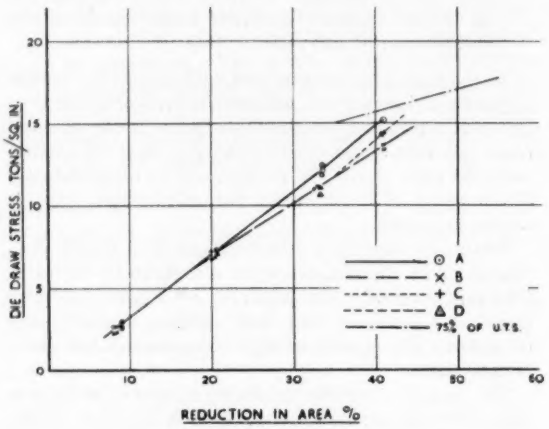


FIG 5

DRAWBENCH TESTS ON ANNEALED COPPER TUBES
12 F.P.M. TUNGSTEN CARBIDE DIE

The maximum limit of reduction in area which could have been effected on these tubes cannot precisely be determined from the die load data only. It is, however, instructive to consider the order of this limit when the die is assumed to bear 75 per cent of the total drawing load. A line has been inserted in Fig 5 corresponding to 75 per cent of the ultimate tensile strength of the drawn tubes, the intersection between this line and the extrapolated draw stress curves giving the estimated limiting reduction in area. On this basis, oils A and B have limits differing by about 10 per cent of reduction, a difference which could profoundly affect the economics of a drawing schedule, since it could mean the difference between the use of three instead of four draws to obtain a reduction of the order of 90 per cent.

COMPARISON OF RESULTS OF DRAWBENCH TESTS WITH BOUNDARY FRICTION TESTS

It is clear from the results of the boundary friction tests that one of the most critical factors in determining the performance of an oil is the temperature to which it is subjected. Unfortunately the effective temperature reached in the zone of the plug and die during tube-drawing is a quantity very difficult to discover. Measurements that have been made (by thermocouple) of the temperature of tubes on emerging from the die gave values ranging between 80° and 140° C, the lower temperature being obtained on copper and the higher ones on its alloys. Although no

unique values can be quoted, it is evident that the temperatures are in the range where lubricants are liable to break down.

The drawbench results show that up to a reduction in area of 20 per cent all the oils behave similarly. This is in harmony with the boundary friction results, which show that, both for tungsten carbide on copper and also for copper on copper, the same coefficient of friction is obtained for all the oils, provided that the temperature does not rise much above room temperature. This condition is satisfied when the reduction is less than 20 per cent and the drawbench speed is only 12 f.p.m.

Under more severe drawing conditions, where the temperature may be expected to rise appreciably, it is found that the plain mineral oil is markedly less effective than the compounded oils. Such a divergence of performance, though not revealed in boundary friction tests of tungsten carbide on copper, is plainly shown in the tests of copper on copper. It may be inferred, therefore, that with the plain mineral oil there was significant pick-up of copper on the tools.

The fact that oil B, containing fatty additive alone, is not revealed as inferior to oils C and D, containing E.P. agents as well as fatty material, even under the most severe of the drawbench conditions used, suggests either the absence of significant pick-up on the die during the draw (cf. Table II) or a temperature below 100° C when the oils behave similarly even for copper on copper (cf. Table I).

It is clear that although there are a number of uncertainties in translating the frictional results obtained in the laboratory into terms of drawbench behaviour, yet nevertheless, in the case of copper (which is the only metal so far investigated in both series of tests), there is harmony between the two sets of results.

No drawbench trials have yet been undertaken to discover how far the detailed inferences from the friction tests, concerning the importance of the time available for reaction and the relative merits of sulphurized and chlorinated additives, are reflected in drawbench behaviour. Obviously a considerable field of work remains for the future.

However, the tests already carried out show that a much fuller understanding of the behaviour of lubricants in tube-drawing can be obtained from a joint consideration of boundary friction and drawbench trials than could possibly be derived from observations of drawing loads alone.

ACKNOWLEDGMENTS

The authors wish to thank Dr D. Clayton for helpful discussions, and Mr T. W. Agar and Mr V. A. Bolwell for assistance in the experimental work.

They would like also to express their appreciation of the co-operation of the Esso Petroleum Co. Ltd. in the formulation and supply of the tube-drawing oils tested.

References

[1] Bowden, F. P., and Leben, L. *Proc. roy. Soc.*, 1939, **A169**, 371.
[2] Rabinowicz, E., and Tabor, D. *Proc. roy. Soc.*, 1951, **A208**, 455.
[3] Wistreich, J. G. *J. Iron St. Inst.*, 1951, **167**, 162.

METAL-WORKING LUBRICATION IN THE BOLT INDUSTRY*

By G. H. TOWNEND

SUMMARY

The present lubrication practice in the fastener industry is very briefly reviewed. It is pointed out that since present practice is satisfactory, the most likely developments will aim at cheaper processing. Mechanical descaling is one such possibility.

INTRODUCTION

BECAUSE of the great range of products covered by the bolt industry it is necessary to define the limits of this paper. It deals with lubrication in the production of bolts, nuts, screws, and nails by cold forging from mild steel wire. While this restriction eliminates all the non-ferrous, high tensile, and hot forged fasteners, it includes quite a high percentage of the total fasteners made.

In general, fasteners are made by cutting off a piece of wire from a coil and cold forging it to shape in a heading machine. The lubrication for this cold working process is almost invariably the lubricant which is applied to the wire for drawing. To consider lubrication in the fastener industry it is necessary to include the cleaning and drawing of the hot rolled rods to convert them to wire for use on the heading machines. An example of the type of operation that

FIG 1

is carried out in a bolt making machine is shown in Fig 1. A piece of wire is sheared off, and the first

* MS received 18 December 1953.

operation reduces the diameter of the wire to the nominal size bolt and partly forms the head. The second operation reduces part of the shank to the thread rolling diameter and completes the formation of the head. The third operation trims the head to a hexagonal shape. It is then pointed and finally thread rolled. All these operations take place on one machine which is known as a " bolt maker."

PRESENT LUBRICATION PRACTICE

It is usual, at present, to clean the hot-rolled rods by pickling, either in dilute sulphuric or dilute hydrochloric acid. The rods are then washed and dipped in a hot mixture of lime and water. The coating of lime then left on the rods serves as a carrier for the lubricant in the wire drawing process, and when it is desired to use a particularly well lubricated wire (as for example for use on a bolt maker) the rod is dipped several times in the lime to achieve a thick coating. The possibility of removing the hot rolling scale mechanically has recently received attention, particularly on the Continent, and more is said about this later. After dipping in lime the rods are flash-baked at about 100° C to ensure that all the moisture is removed before they are drawn. The rods are then drawn into the wire using a dry soap as a lubricant. The commonest soap in use is ordinary brown sodium soap, but in certain applications metal stearates are sometimes used. Calcium and aluminium stearates are probably the most common. The wire may be drawn through one or more dies, and if the wire is being multi-holed dry soap boxes are provided before each die. It is, however, very noticeable that very little fresh lubricant is picked up after the first soap box.

The factor which should be stressed about drawing wire, as outlined above, is how well the process works. Die life is such that the cost of dies is a negligible part of wire production costs. Further, the limitation of speed on drawing is more likely to come from the drawing machinery side than from difficulties of lubrication, and indeed there does seem to be some evidence that lubrication may improve with speed.

POSSIBLE DEVELOPMENTS

One possible development which has received considerable attention recently, particularly on the Continent, is the drawing of mechanically descaled rod.[1, 2] In this process the bulk of the hot rolling scale is removed from the rod by bending it. The relatively brittle scale is unable to follow the plastic flow of the steel and flakes off. A light brushing removes loose scale particles.

If the descaling process is envisaged as combined with the drawing process, then considerable savings are possible. However, it is found to be considerably more difficult to draw mechanically cleaned rod than pickled and limed rod, particularly at high speeds, say above 1000 f.p.m. This factor probably explains the reason for the method finding greater favour on the Continent, where finishing speeds do not in general exceed about 800 f.p.m.

As it is not easily possible to lime the wire in between mechanical descaling and drawing, it is usual to use as a lubricant a mixture of lime and soap. André Line [1] details many of the factors which help in the drawing of descaled rods such as correct die profile, adequate cooling on the dies, and so on. Even when all these measures are taken, mechanically descaled rod is still much more difficult to draw than the pickled rod. The reason for this is not very clear. Line ascribes it to the rougher surface of the mechanically descaled rods.

For a satisfactory solution to this problem the wire should not only draw with reasonable die life, but should also be satisfactory in subsequent processing. Nail making is a particularly sensitive operation in this respect. Unless the surface lubrication of the wire is good, unsatisfactory operation of the cutting off dies is experienced. The dies are in the form of two wedges which indent the wire from opposite sides. With satisfactory wire the wire fractures while the dies are about $\frac{1}{50}$ inch apart. This cut-off gap is greatly reduced with mechanically descaled wire, and the consequent need to set the tools closer results in unsatisfactory tool life.

A second avenue of development, which has received considerable attention recently, is the phosphating of wire. While this process is fairly widely employed for drawing high carbon and shape wire, it is not generally used for round mild steel wire. The reason for this is that, while phosphating would no doubt show some gains in the drawing of mild steel wire, they would not be sufficient to cover the extra cost of phosphating. However, it might be that the savings gained on later processing would justify the cost where this could not be justified by savings in the drawing process alone. For example, in bolt making some improvement should be obtained in extruding, heading, and thread rolling die life. A further gain would be the increased corrosion protection for wire which is stored between drawing and heading. Against this most fasteners are made from wire in coil form. No surface treatment in coil form assists in the lubrication of the end of the blank, so that no assistance can be obtained from phosphating, for such relatively difficult work as Phillips recess forging. Perhaps the strongest reason for using phosphating is that in certain cases it will allow the forging of shapes which are impossible without it, and a further realization of the potentialities may widen the field of use in the fastener industry.

References

[1] Line, A. *Wire Ind.*, 1953, **20**, 66.
[2] *Draht*, 1953, **4**, 95–7.

DISCUSSION

Dr C. B. Davies: I will now ask Professor Thompson if he will give us his summing-up of the papers on the subject of Metal Forming.

Professor F. C. Thompson: It is perhaps not altogether inappropriate that this discussion should be opened by a member of the University with which Osborne Reynolds himself was for so long associated.

To the more industrially minded members of this audience, perhaps nothing will convey the importance of lubrication more than the tests recorded, and the observations made, by McFarlane and Wilson. The difference between a merely satisfactory, and a really good lubricant, so far as the drawing load is concerned, may be small, but in terms of frictional loss the difference may be really important. The authors would, I am sure, be the first to admit that in their discussion of Fig 5 there is an element of the hypothetical. On the basis of their argument, however, which seems to be eminently rational, they show that a comparatively small difference in the drawing load may be due to a frictional effect which might profoundly affect the whole economics of the production scheme by varying the number of passes which are possible, and thereby increasing, or reducing, the number of intermediate annealings which are required.

Inadequate lubrication—even where the operation may appear to have been satisfactorily accomplished—may have most detrimental metallurgical consequences in the overworking of the surface, and thereby the setting up of severe, superficial tensile stresses leading to premature failure through fatigue.

The wide range of lubricating materials employed by the metallurgical engineer is well illustrated in the paper by Perry. Even this list, however, is not by any means complete, and even such an unexpected material as molten glass finds industrial application. It is, in fact, the only lubricant at present known which permits the extrusion of certain alloys which must be worked at very high temperatures.

A number of aspects of the general problem crop up in paper after paper, and it may be well to consider these first of all. One of these is the real nature of the lubricating film, and on this point there appears, as yet, to be no complete unanimity, probably because the conditions vary so much from process to process. Bowden and Tabor, for instance, remark that the "pressures involved in most metal-forming operations are too high for hydrodynamic lubrication . . . to be attained with conventional lubricants"; Christopherson, Naylor, and Wells, that "much of the work suggests that the state of affairs is in many cases intermediate between what would ordinarily be regarded as boundary lubrication on the one hand and fluid or hydrodynamic on the other." This is in agreement with the remarks of Ranger and Wistreich for wire-drawing, and of Perry in the case of the drawing of tubes, and is, incidentally, the conclusion reached by Baron and myself in a paper which is mentioned by several contributors. There are, however, undoubtedly cases, in wire-drawing at any rate, where full fluid lubrication is attained. No one could stand at the exit end of a die through which heavy gauge steel wire is being drawn at high speed, and see the flakes of soap emerging and breaking away from the surface, and still have any doubt on this point. Taking the evidence presented as a whole, it would appear that the speed of the process is one of, perhaps the major, factors involved, and as this speed is raised, the thickness of the film progressively increases.

This question of the speed of the operation may perhaps provide an explanation, in part at any rate, of the need stressed by Sims for a range of different lubricants specially devised for each specific type of operation, a need of which the Companies, to judge from the papers of Perry and of McFarlane and Wilson, are well aware, and are endeavouring to meet.

The surface temperature attained during the process has for a long time been recognized as the factor which perhaps more than anything else limits the severity of the deformation which can be imposed. Bowden and Tabor discuss this is detail and the suggestion of the desorption of the liquid film at a temperature above the melting point, but below that at which chemical decomposition of the lubricant occurs, may throw considerable light on the results of certain high temperature drawing tests. The marked increase of friction which they show to occur at the melting point of metallic films reflects almost exactly what has been observed with soap lubrication, though in the latter case the result was misinterpreted and ascribed to chemical decomposition.

The nature of the dilemma will now be apparent. So far as lubrication *per se* is concerned, the evidence which is put before us, and which is in good accord with what is already known, suggests strongly that the higher the speed of the operation, the better. At such speeds, however, the temperature rise is increased due to the increased rate of development of heat due to the deformation itself, and as a result of this increased temperature, break-down of the lubrication tends to occur. It is, therefore, a matter for most careful compromise on the part of the engineer, and at the same time provides a most important field for the development of lubricants of great thermal stability on the part of the oil technologist.

Many contributors to this symposium have pointed out the importance of the nature of the metallic surface, both mechanical (Ford and Ranger and Wistreich) and chemical (Bowden and Tabor, Perry, and McFarlane and Wilson). The importance of gases on the surface is most clearly demonstrated by Figs 7 and 8 of the paper by Bowden and Tabor, who also point out the importance of the mechanical properties of the underlying material in providing adequate mechanical support for the oxide, or other, film. The justification for this is fully evident to all concerned with the production of case hardened parts, who know only too well that it is the elastic failure of the core which generally results in the subsequent fracture of the case.

While we are considering the reduction of friction by improved lubrication, it is important to remember that in certain metal-working operations, *e.g.* in rolling, a certain amount of friction is essential. In the absence of such friction the metal could not be drawn into or through the rolls, and the search for lubricants with lower and lower coefficients of friction must reach a point when a further reduction would have detrimental, rather than beneficial, effects. Professor Ford may possibly have reached this point.

All the contributors to this symposium are in agreement regarding the severity of the stresses which may be set up between the work and the die, and Professor Ford makes a most pertinent point when he asks, "What happens to their physical properties at such pressures?"

A partial answer is given by Bowden and Tabor, who state that in the case of long-chain organic compounds the strength increases enormously as the pressure is raised, so that liquids become extremely viscous or even plastic solids, and that soft, waxy materials become hard and brittle. There is here a field of research, probably of very great experimental difficulty, which must be of the greatest interest to the pure scientist, to the metallurgist, and to the engineer.

One physical property which receives little, if any,

attention in these papers is the tensile, as distinct from the shear, strength of the lubricating film. In offering an explanation of the oscillatory nature of the records which they have obtained, Ranger and Wistreich ascribe these to surface imperfections of the wire being drawn. Such surface irregularities will clearly have the effect observed, but it is interesting that when these curves are examined, and compared, for instance with those of Christopherson, Naylor, and Wells, or particularly those of McFarlane and Wilson, to note the regularity of the effect. If the explanation is to be found merely in surface imperfections, which could hardly be expected to be other than erratic in their location, the relative regularity of the changes seems a little bit difficult to understand.

The break-up of the lubricating film, which is, perhaps, the main reason for the electrical resistivity measurements carried out by these authors, has been shown by Macaulay * to be dependent on surface forces, as would be expected, but this instability must also be controlled by the tensile strength of the liquid film. It would appear to be self-evident that the higher the tensile strength of the film, the more resistant it should be to break-up and the more effective, therefore, other things being equal, as a lubricant.

Is this too fanciful to see one cause of the oscillations which all three sets of workers have found, even when drawing appears to be reasonably smooth, in the repeated failure of the film under tensile stress and its subsequent reformation ?

Any data on the variation of the tensile strength of these films would seem therefore, to add much to our knowledge of lubrication under very high pressures, and to offer a field of research, possibly of outstanding importance, which has, as yet, been very inadequately explored.

In regard to the papers, these are introduced in a most excellent summary, by Bowden and Tabor, of the present fundamental position, much of which is due to work in Dr Bowden's own laboratory, and which has been accepted by so many of the other authors as the basis for their own arguments. In addition to the points which have already been mentioned, they emphasize that if soap films contain an appreciable amount of water, ebullition may occur at temperatures above 100° C, and the film then loses its lubricating properties. This face has been appreciated in the drawing of iron and steel wire for a very long time, and at times the soap has been stored for over a year before use. These authors, like McFarlane and Wilson, also discuss the relative advantages of extreme pressure lubricants containing sulphur and chlorine. Their mention too of plastics and molybdenum sulphide is an indication of the widely divergent types of material which possess potential lubricating qualities.

The paper by Townend on lubrication in the production of steel bolts is valuable from the emphasis that it lays on coating with lime, and the advantages to be gained by producing a coat of adequate thickness by repeated dipping. He also makes the interesting observation that it is found to be considerably more difficult to draw mechanically cleaned rod than that which has been pickled, particularly at speeds above 1000 ft/min. Nail-making and the phosphating of wire are also discussed, and in connexion with the latter it is remarked that in certain cases phosphating will allow the forging of shapes which are otherwise impossible to produce.

The contribution by Professor Ford contains a short note on a new method of measuring the friction in rolling, the great advantage of which lies in the fact that the friction is measured under the conditions which obtain in the rolling process itself. The list of results given in Table II is of interest in several respects and demonstrates clearly the reduction in the coefficient of friction as the surface becomes progressively smoother. Conclusion 5, p. 293, indicating that "lubricants which give low values of the coefficient of friction leave the strip matt and dull," might have been expected, but that "in many cases there is then serious surface damage" is a most important and probably unexpected result. The further work which is promised on these lines will be looked forward to with considerable interest.

The paper by Loxley and Freeman is an important contribution in regard to the field of lubrication in deep drawing. The relatively low speed at which most of such operations are carried out makes satisfactory lubrication an especially difficult matter, but a comparison of Fig 5 (*a*) and (*b*) of their paper provides the most convincing evidence of its significance in a field of work of great and growing importance. The apparatus for this work has clearly been very well designed, and one may look forward with interest to other work from a School which, under Professor Swift, has made a special study of this process of deformation.

In addition to the matters already discussed, the paper by Ranger and Wistreich is of value in the information which it provides regarding the absolute values of the thickness of the lubricating film. Even if an element of uncertainty still persists, the fact that these authors are able to state that "the film thickness oscillates between, say, 1000 and 30,000 Å" is a clear indication of the fact that knowledge in this field of study is making substantial progress.

The paper by Sims on lubrication in cold-rolling presents a well balanced and clear exposition of the subject. In particular, it is shown, though not for the first time, why an increase of the horizontal force due to the frictional effect should have such a marked effect on the vertical stresses. This is linked up with the measurements given in Tables II and III for the variation of the thickness of the strip with the speed of rolling, and with Fig 2, which presents in a very clear visual manner the reason for this change of thickness with the coefficient of friction. The author concludes that there is reasonable evidence to support the view that the change in coefficient of friction with speed is due to a variation of thickness of the film of lubricant.

Important as lubrication is in the drawing of wire, it becomes even more so in tube drawing, where two surfaces have to be considered. The papers of Perry and of McFarlane and Wilson provide a large amount of information, which cannot fail to be of industrial value. Perry reviews the type of lubricants employed for a wide range of materials, and is the only author to draw attention to the necessity of the lubricant being such as not to lead to staining if the metal is subsequently bright annealed. This may appear a triviality, but is in fact a matter which is at times of serious difficulty.

McFarlane and Wilson's contribution discusses at some length the question of the influence of the time of contact of the metal and the lubricant before the deformational process is carried out. In Table I and Fig 4 the importance of this factor is clearly revealed, particularly in the higher temperature zone. Thus at 180° C for oil A, the coefficient of friction, which is 1·5 for a short period of exposure, falls with time to 0·05. The anchoring of the molecules of the lubricant to the metal, at any rate with the normally contaminated surface, is clearly not instantaneous, and methods of speeding the process up in industrial operations might form a subject for useful discussion.

Finally, the paper by Professor Christopherson, Naylor, and Wells is one of particular interest, especially

* Macaulay, J. M. *Engineering, Lond.*, 1926, **122**, 619 and 654.

in connexion with the work done on the forced lubrication of the die in wire-drawing. The original suggestion of MacLellan and Cameron has been applied in a most interesting manner to the production of relatively thick films in which full fluid lubrication can exist. This is clearly one of the most outstanding developments which has been made in recent years in the field of metallurgical lubrication, and valuable results in practice may be expected from its application in specially difficult drawing operations, whilst the technique also appears to be applicable to the cold rolling of especially hard materials.

The majority of the papers with which we are concerned this evening have tended to look on lubrication in its more or less classical attire. The fact, however, should not be overlooked that under the very high pressures which obtained in many metal-working operations, abnormalities do occur, leading to marked deviation from classical theory. To those who, like myself, are not experts in this field of oil technology, reference may perhaps be made to a paper by Mardles.*

Our gratitude must be extended to all the authors of these papers for their important contributions and the trouble to which they have clearly gone in producing them. I must extend to them my own personal apologies for the inadequacy of these summaries, but it is proverbially difficult to get a quart into a pint pot. With the single exception of the extrusion process, all the major methods employed in the working of metals have been passed under review, and these papers, and the discussion which is now about to take place, cannot fail to be of value to the metallurgical engineer, and will, one may hope, enable the producers of lubricating materials still further to improve their products.

Dr J. W. Jenkin: It has been said that progress has sometimes been handicapped by a difficulty in speaking a common language and in really getting down to scientific facts together. Any opportunity, such as this symposium affords, of exchanging opinions and getting to know each other's point of view is very much to be welcomed. The adoption of a common language is facilitated by the use of terms which both parties in some measure understand. When those of us concerned with the metal being worked describe it as mild steel, or stainless steel, or copper, or aluminium, the experts in lubricants have a fair idea what we mean, when our friends talk to us in terms such as Shell P.E. 6, or Esso 885 pale, or Vacuum 40A, we are being addressed in riddles. Even metallurgists have an elementary knowledge of chemistry, and expressions like "paraffin oil plus 1 per cent oleic acid" mean a little more to us than a mere number.

My concern is with the cold working of metal tubes in steel and in aluminium alloys, and it will be clear therefore that most of my remarks relate to the papers by Mr Perry and Messrs McFarlane and Wilson. My colleagues and I have read and discussed these papers with great interest and profit, and where we differ in some respects I would say that our point of view is that of questioners rather than adverse critics. Indeed, we feel that both papers are of great merit. Mr Perry has given us a review of current practice in tube drawing that is in all essentials an excellent account of what is done today.

There are one or two points of detail where his account is hardly in error, but is perhaps incomplete. Early in the paper he correctly says that most cold drawing is carried out on straight-pull drawbenches. As sizes increase, of course, this becomes impracticable, and the tube has to be pushed by the mandrel that supports the bore. Since what matters is the relative movement between tube and tools, for very large diameters, up to say 26 inches (the maximum now made in this country) the most convenient way is to hold the tube on a bar and push the die over it. Such operations on large tubes are, of course, done on hydraulic benches.

Mr Perry's references to the reductions in sinking, at the top of column one, p. 320, are rather pessimistic. A diameter reduction of 20 to 25 per cent would be regarded by us as low. Indeed, reductions twice as heavy can be achieved provided the die is so designed that it does not wipe the lubricant off and does not induce complex residual internal stresses in the tube. He refers in mandrel drawing to a slight taper being ground on the mandrel, but except in large sizes our experience is that reeling off a parallel mandrel offers no undue difficulty. Mr Perry says that a final sink may be given after initial mandrel or plug draws; true, but this wants to be done with knowledge and care, or unsatisfactory results may ensue. I would differ from Mr Perry when he says at the end of p. 320 that the good finish to the tube is not so important as with wire and rolled strip, for the tubes are often polished afterwards. Certainly they can be, but that is a costly added operation which is applied to an only extremely small fraction of the tonnage (or footage) of the cold drawn steel tubes produced. I agree with him, however, that the cooling effect of the lubricant is not often important. How right he is when he says that what the exact state of lubrication is in cold drawing cannot be said to be completely established. For all our ignorance I am rather more in sympathy with Mr Perry than I am with Messrs McFarlane and Wilson in their statements of what a good tube drawing lubricant should do. Mr Perry says (in this order) heavy reductions, long die life, and good finish; Messrs McFarlane and Wilson say reducing friction, long die life, and cooling the tools. We doubt whether friction is an all important factor. The job of a lubricant is to enable us to produce economically a tube that can be sold. It must keep the tube and tools apart to give a good finish. It functions only as a lubricant instantaneously, *i.e.* once only in every element of tube length, though under high pressures. We doubt, for example, whether Messrs McFarlane and Wilson tell the complete story when they regard drawbench load measurements as the final criteria, and use a boundary friction apparatus as a means of obtaining experimental data. Granted that these are necessary and valuable, in our experience we have sometimes had better results in drawbench production with lubricants that give high figures for coefficients of friction. We wonder, too, whether this is not borne out by Messrs Loxley and Freeman in Fig 12 of their paper. It is true that they are dealing with what they call ironing, which, however, is not very dissimilar from mandrel drawing a tube. In their illustration the tractional load is much less with graphite and tallow, but it is to be noted that the cups broke sooner with this lubricant, and the authors could not get reductions as great as those obtained when using a lubricant with presumably a lower coefficient of friction.

Drawbench load measurements are most useful, but they cannot take account of some features that cause rejection, such as die or plug lines. Slider experiments seem to us to be of limited value too, for although fundamentally they have much in common with tube drawing, I doubt whether copper sliding on copper can be regarded as simulating tube drawing conditions.

In all these matters, the greatest difficulty is to take care of all the variables that can make or mar success in actual tube production. Messrs McFarlane and Wilson refer to their experience that on a full-size automatic bench the performance of a lubricant was not as good as their sliding experiments suggested. We would go further and say that there is also a difference between

* Mardles, E. W. J. *Oil, Lond.*, 1954, **2**, 20.

drawbench experiments under laboratory control and drawbench production in ordinary. This in our minds is associated with features that perhaps have not received sufficient emphasis in these papers: the importance of the preparation of the tube before lubrication. As the Chairman so rightly said in opening the first session, lubrication is but one of several factors affecting tube production. Poor initial surface, ineffective pickling, extraneous dirt, and so on can be of vital importance. So can the shape of the tools and even the design of the bench. Chattering, for instance, may be a function of the construction of the framework of the bench itself as well as of the elastic properties of the bar supporting the plug. There are, moreover, effects of the humidity and temperature of the atmosphere, and of the time elapsing between lubricating and drawing.

Dr A. Cameron: I have been very impressed by the similarity between the frictional phenomena of gears and metal forming. In gears the coefficient of friction also drops with speed to about 0·04, exactly as described by Sims.

It seems that the frictional properties can be explained by the hypothesis that there is a coherent oil film some 10,000 Å thick and that the amount of boundary friction is relatively small. This value of the oil film thickness agrees with the results obtained by Ranger and Wistreich.

I have found that the oil film between gear teeth can be investigated by measuring the voltage drop across the oil films under conditions of constant current, instead of the usual method of constant voltage, in the following way:

In a steadily running disk machine if current is plotted against voltage, the following type of curve results:

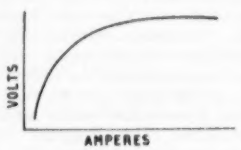


FIG A

This is an alternative method of plotting results shown in my paper to the Institute on 10 March 1954, which contains fuller details of these points.

This shows that the volts increase steadily to a maximum, and however much more the current is increased, even up to 320 amp, the voltage across the oil film does not increase, once a discharge, with its consequent ionization, has started.

This type of curve is found with lightning arrestors, and is well known in high voltage transmission work. The voltage can be taken as a measure of film thickness.

It would appear from Christopherson's paper that he has found the breakdown voltage to be about 2 volts. This simplifies very considerably the method of using the electrical measurements. If the current chosen is high enough to ensure the maximum value of voltage has been reached, the voltage drop will be a direct measure of the film thickness.

I hope to work further on this problem. The same type of oil film has been found in some work I have been connected with on oil seals, where the results can be explained on the hypothesis of a coherent oil film.

It is also rather convenient to find that the same laws of friction apply to gears as well as wire drawing.

I am glad to see that Christopherson's wire die pump experiments have revived an idea I thought, alas, had died ten years ago. I should be interested to hear how he gets over the trouble which killed it then, *i.e.* the removal of swarf. In the oil pump we tried, which was aimed at producing a high oil pressure in order to force oil through the die and thereby promote full fluid lubrication, the whole tube got choked with swarf, which we could not remove.

J. G. Wistreich: I have a feeling that the brilliant researches of Dr Bowden and his Cambridge School concerning dry friction and boundary lubrication are exerting an undue influence on investigators in the field of metal forming. I do not wish to suggest that their work is not highly relevant to the subject under discussion, but I do think that we are getting on to the wrong track by treating metal-working processes as instances of pure boundary lubrication. I note that Drs Bowden and Tabor agree with me there, and I should like to indicate some of the reasons why I feel that in this field we would do well to concentrate our attention on the theory of thin film or quasi-hydrodynamic lubrication.

There is no need for me to discuss wire-drawing lubrication from this point of view, because the paper by Professor Christopherson and his colleagues speaks for itself. Here you have an example of what can be achieved by not taking the cue from the theory of boundary lubrication. I would only add, for those interested in the subject, that in my laboratory we are at the moment applying forced lubrication on a high-speed industrial machine, both with oil and with soap powder as the lubricant.

Professor Ford's paper, in discussing the impressive difference in μ between the slider test and the plane compression and cigar tests, points out that in the latter two tests the metal is being deformed in bulk, and feels that the reason for the difference in μ is to be sought in this. I should like to suggest that the cause lies elsewhere. The slider in the Bowden test is a hemisphere of small radius, a shape which discourages hydrodynamic lubrication. On the other hand, the configuration of the plane compression and cigar tests lends itself to the trapping of lubricant. In fact, the appearance of cigar specimens suggests that this occurs, because the surface is matt, except for a narrow shiny band round the edge. Thus I am inclined to say: μ in the Bowden test is relatively high because this is a geniune case of boundary lubrication; the other tests are cases of a mixed régime of lubrication with a correspondingly low μ.

Likewise I would suggest that the drop in friction on repeated rolling, recorded by Professor Ford in his Table II, is the result of increasing smoothness of the strip which encourages quasi-hydrodynamic lubrication. I am certainly not happy about Professor Ford's stress-analysis, because the value of s is conditioned more by local conditions in the vicinity of the junction, *e.g.* constraint by trapped lubricant and geometry of junction, than by the bulk properties of the deforming metal. I must also confess that I am at sea about the derivation of the stress formula—but this is a little outside the scope of our discussion.

I do, however, strongly agree with Professor Ford, about the urgent need for knowledge of the high pressure physics of lubricants. Incidentally, his attempt at correlating μ and surface finish is most intriguing, and I keenly look forward to an elaboration of the conclusions quoted, for clearly they are of the greatest practical interest.

Now, Mr Sims has placed us in his debt by marshalling clear evidence for the connexion between speed effect and friction and the dependence of the latter on roll finish. But his suggested explanation of the effect will, to say the least, be received with mixed feelings. Surely we have suffered enough from "lubricity" and "oiliness!" Must we now buy "extrudability, fast and slow," and shall we pay for crystallizing additives?

I sincerely hope not, and on the strength of the evidence placed before us I see no need for it. Indeed, I would suggest to Mr Sims that he make use of Occam's

razor and that he be content with having discovered that lubrication in rolling is quasi-hydrodynamic.

Let us look at the evidence. Table II tells us about the effect of roll finish. I have made the following calculations from it :

$$\frac{\mu_{294}}{\mu_{53}} = 0{\cdot}68_{(\text{a mirror})} \quad \frac{\mu_{296}}{\mu_{51}} = 0{\cdot}60_{(\text{a matt})}$$

$$\frac{\mu \text{ rough}}{\mu \text{ smooth}} = 1{\cdot}29 \text{ at } 50 \text{ f.p.m. and } 1{\cdot}25 \text{ at } 300 \text{ f.p.m.}$$

These figures tell us that the effect of speed on friction is much the same whatever the roll finish, but the value of μ depends on the roughness of rolls. This is well in accord with the concept of thin film lubrication, for which surface roughness is of the cardinal importance. In Fig 4, the issue is confused by the use of the word " solid " in the legend of the figure. The interpretation is quite straightforward if one refers instead to Mr Sims' careful account of his experimental procedure. Taking the curves from top to bottom, C was swabbed with a suspension of MgO. It shows the same absence of a speed effect as Sims and Arthur's experiments with solid graphite, talc, and vermiculite. I assume that these solids have no viscosity, and therefore the film thickness is not speed dependent. Now the strip used in A, B, and D had no MgO on them, and all show the speed effect. A and D are indistinguishable at high speed, A and B at low speed. What was the important difference in the treatments ? Surely, the quantity of oil. If there is a lot of oil on the strip, then the speed effect is pronounced ; if we remove some of it with benzine, then it is attenuated, and if we pump oil into the roll gap, then friction drops to a low value at quite a low speed.

All this fits in very nicely with the concept of the thin film or quasi-hydrodynamic régime. There is one further piece of evidence in support of this idea. The speed effect does not occur universally ; for instance, we cannot get it in our Sheffield laboratory when rolling with small rolls. It is particularly pronounced in the fifth stand of a tin plate mill, where the rolls are large and appreciably flattened owing to the hardness of the strip. With a large and seriously flattened roll the wedge angle is smaller, and thus the hydrodynamic lift more powerful.

I am aware that Keller has tried to show that hydrodynamic lubrication is not possible in rolling, but in his calculations he neglects elastic deformation of roll and strip at entry and he does not allow for the effect of pressure on the viscosity of oils.

Mr Sims is right in drawing attention to the presence of chemical reactions of the kind examined by the Bowden school. Therefore, I am at one with him in thinking that the relevant properties are not those of the lubricant in the drum but in the roll gap, contaminated by reaction products. Surely, his extrusion, fast or slow, is nothing but a hydrodynamic lift, and the appropriate property of the lubricant its viscosity.

If I am right in supposing that lubrication in metal forming is not of the pure boundary type, but is usually in the thin film régime (and may be forced into the thick film régime), then it is clear that not only do we need to consider surface chemistry and local temperature, but must also take into account the configuration of the sliding surfaces and the bulk properties of the contaminated lubricant.

I cannot help but point a finger at members of this Institute, which I look upon as the fortress of lubricant chemists : we need to know what sort of reactions occur at these high pressures, and what is the required viscosity of lubricants and of the reation products at high pressures. Judging by the papers before us, the physicists and engineers seem to have this field to themselves. I hope the chemists will shed their modesty during the discussion, and prove to us that they have the answers up their sleeves. If this is not the case, then I am forced to repeat : until the chemists get down to this high pressure study the research effort will continue to be lop-sided and the industry will have to carry on sampling proprietary mixtures on a hit or miss basis.

L. H. Butler : Professor Ford, in his paper (p. 293, conclusion 5) states that lubricants which give low coefficients of friction leave the strip matt and dull. This statement does not seem to be complete without reference to the lubricant viscosity. If a strip of material is compressed using a lubricant of low viscosity and low coefficient of friction, the surface finish remains bright, but if a lubricant is chosen with a high viscosity meanwhile retaining a similar low coefficient of friction, then the strip surface deteriorates, indicating that the bulk properties of the lubricant influence the surface finish obtained. Professor Ford continues, " In many cases there is serious surface damage, not so much by ploughing action but by tearing of particles out of the surface." It is not quite clear whether this surface damage is additional to the strip surface being matt, or whether the matt surface is directly attributed to the tearing out of particles. It is assumed that the former is intended, in which case the additional damage is difficult to account for, since the production of the matt strip must be associated with the presence of a relatively thick lubricant film and consequently relatively little intermetallic contact between roll and strip. This matt surface finish effect can be observed on strips of aluminium subjected to plane strain compression tests. In such a test, for any given load and lubricant, the strip will experience a specific percentage compression dependent on its mechanical properties. This compression is probably an indirect measure of the coefficient of friction between platens and strip. If such plane strain compression tests are carried out with a series of non-reactive lubricants of varying viscosities, it is found that a bright surface finish is obtained with the lower viscosities and, as the viscosities increase, the strip surface becomes progressively duller. In general, as the viscosities increase the amount of strip deformation experienced also increases, implying a decrease in coefficient of friction. Thus, in summary, increasing viscosities are associated with deteriorating surface finish and decreasing coefficients of friction. After such tests, if the platens are wiped with a clean filter paper it is found that a black detritus is left on the platen surface, which is presumably either finely divided oxide or virgin metal torn from the aluminium surface. The amount of loose detritus appears to be greater with the poorer lubricants than with the better, and indicates that the matt surface is not associated with removal of metal. It is suggested that with the more viscous lubricants, a thicker film is trapped between platen and strip and the pressure causing deformation of the strip is largely transmitted through the oil film itself, which may, at extreme pressures, even become solid. The matt surface may be the result of inhomogeneous deformation of the strip due to the varying orientations of the individual crystals plus slip within the crystals themselves.

An unexpected effect has recently been observed if successive new indentations are made on a strip using the same lubricant and load without cleaning the platens. It is found that for the second and subsequent impressions, greater deformation of the strip is experienced than with the initial impression. The reason for this has not yet been positively confirmed, but the existence of the effect indicates that caution should be exercised when measuring coefficient of friction by the plane strain technique, since the use of thoroughly cleaned platens may give rise to a higher coefficient of friction than would be experienced under working conditions.

Mr Sims in his paper does not accept that the thicker

lubricant film between rolls and strip at high rolling speeds is induced by hydrodynamic effects. Beek, Givens, and Smith (1940), Forrester (1946 and 1947), and other workers have shown that hydrodynamic or quasi-hydrodynamic effects can be experienced with boundary lubricants at high pressures even at moderate sliding speeds. The bulk contours of the roll and strip are not conducive to conventional hydrodynamic film formation, but neither is the die in the wire-drawing process. Professor Christopherson and Mr Wistreich, however, both suggest that some degree of fluid lubrication is possible in this process, and it is suggested that the establishment of a thick film in the rolling process by hydrodynamic or quasi-hydrodynamic means cannot be dismissed, especially since use of a viscous lubricant results in the production of matt sheet, which appears to be associated with the existence of a relatively thick film of lubricant.

D. A. Barlow: Part I of Messrs Loxley and Freeman's paper on "Some Lubrication Effects in Deep Drawing Operations" deals with the so-called anomaly in the deep drawing of aluminium and other metals. The first part of the anomaly, *i.e.* that the soft tempers draw better with a hemispherical punch than with a flat one and vice-versa for the harder tempers, is rightly attributed in some way to the stress–strain–strength properties of the materials. The second part of the anomaly concerning aluminium, *i.e.* that the harder tempers often give better results with a flat-ended punch than the softer ones, however, is attributed wholly to the lubrication conditions. It is obvious that if a lubricant which gives relatively low dynamic friction (and perhaps high static friction) with the harder tempers and relatively high dynamic friction with the softer tempers is used, the harder tempers will draw best, and vice-versa. The difference in drawability obtained with the three lubricant conditions used by Messrs Loxley and Freeman can only be explained on this basis. However, that the harder tempers of aluminium draw better than the softer tempers with the flat-ended punch under some conditions can be explained by the stress–strain–strength properties of the materials.

In deep drawing with a flat-ended punch the punch load is governed largely by the compression properties of the material. The ability of the cup to withstand this load is governed largely by the ultimate tensile stress of the material. There is no reason why the ratio of ultimate tensile stress to compression properties should be higher for soft than for hard tempers; in fact, the reverse is the case, and softness and tensile ductility have practically nothing to do with deep drawability with a flat-ended punch. This can be seen in the true stress–strain curves given by Chung and Swift * for soft and half-hard aluminium; the curves approach each other closely at moderate strains in spite of the large difference in proof stresses and ultimate tensile stresses. Further, the soft aluminium reaches its maximum load in deep drawing when it has been work hardened considerably, whereas the half-hard temper reaches its maximum load early in the draw. These characteristics are shown by other work-hardening aluminium alloys and by heat treated alloys. If the total drawing load is calculated, using Chung and Swift's theory, and the ultimate tensile stress taken for the cup wall strength, assuming that failure takes place in the parallel walls, the deep-drawing properties of the alloys can be obtained, and again, the harder material is superior, if the same coefficient of friction is used in each case. The calculation of the cup wall strength in this way is very crude, but it gives better agreement with practical results than might be expected at first sight. Moreover, it can be shown that failure will occur near the junction of the walls with the punch profile radius if the coefficient of static friction over the punch head is greater than about 0·3, depending on tool dimensions. If the coefficient of static friction is less than 0·3, failure will take place at a lower load somewhere over the punch profile radius.

To obtain the maximum deep-drawing properties, therefore, the coefficient of static friction over the punch should be high and the dynamic friction over the die and blankholder low. It seems that a straight mineral oil would most nearly satisfy these requirements at practical speeds of drawing (unlike the low speed used by Messrs Loxley and Freeman). The viscosity of the oil would be chosen to suit the speed and pressure of the operation, giving hydrodynamic or some sort of thick film lubrication over die and blankholder, but as the oil would possess little or no boundary lubrication properties, it should not reduce the static friction over the punch. In practice, plain machine oil containing no boundary lubricant except for a maximum of 2 per cent of waxes are often used for deep drawing aluminium, perhaps because they most nearly conform to these requirements. As evidence that some sort of thick film lubricant is operative in deep drawing, the surface of a cup which has not been ironed show the typical matt finish obtained with thick films, as opposed to gross scoring with poor lubrication, or a burnished surface obtained with thin film lubrication. As hydrodynamic lubrication only is required, almost any substance of suitable viscosity could be used. Isachenkov † has found this to be the case—there is an optimum viscosity for a given drawing speed, and pressure and such unusual lubricants as sugar and gelatine solutions of suitable viscosity were satisfactory.

In deep drawing operations with a flat ended punch, the maximum reduction obtainable is that at which the maximum punch load during the draw does not exceed the strength of the cup walls and base in tension, provided that certain other requirements, such as sufficient compressive ductility, are fulfilled. Punch loads can be accurately calculated from Chung and Swift's * theory, and if the strength of the cup in tension could be calculated, the deep drawing properties of the material could be ascertained. However, it can be shown that provided the coefficient of static friction over the punch head is fairly high, above about 0·3, failure will not take place over the punch profile radius, but will occur near the junction of the parallel walls with this radius (even when the die profile radius is large). The strength of the cup walls under these conditions could no doubt be calculated accurately, but is given with fair approximation to practical results by the simple ultimate tensile stress (U.T.S.) of the undrawn material. In any case, whatever the position or conditions of fracture, the failing load will be roughly proportional to the U.T.S. of the undrawn material. The major portion of the punch load is that required to form the cup walls by the circumferential compression of the blank. The compression properties of the material, therefore, largely determine the punch load. Thus, for good deep drawing properties a material should have a high ratio of U.T.S. to compressive properties. Very little tensile ductility is required in deep drawing with a flat bottomed punch, and there is no reason why soft materials should have higher values for the above ratio than hard ones—in fact, the reverse is usually the case. In other words, the compressive stress–strain curves for different tempers tend to converge at moderate strains. This can be seen

---

* Chung, S. Y., and Swift, H. W. *Proc. Instn Mech. Engrs*, 1951, **165**, 199–223.

† Isachenkov, E. I. *Vestnik Mashinostroyenya*, 1951, **10**, 60–8.

in the true stress–strain curve given by Chung and Swift* for the soft and half-hard aluminium. Furthermore, the superiority of the harder tempers is accentuated by the fact that the maximum load is reached early in the draw, whereas for the softer tempers the maximum load is not reached until the material has been work-hardened considerably, *i.e.* as it approaches the harder tempers.

In a practical example of a 50 per cent reduction $\left(\frac{\text{blank diameter} - \text{punch diameter}}{\text{blank diameter}}\right)$ in soft and half-hard aluminium, the mean compressive stresses at the maximum load are about 6·7 tons/sq. in. and 7·7 tons/sq. in. compared with U.T.S.s of about 5·5 and 7·5 tons/sq. in. respectively, giving ratios of 0·82 : 1 and 0·98 : 1, *i.e.* the half-hard aluminium is superior. The actual magnitude of this difference is affected by other factors, such as bending over the die radius, etc., but the half-hard aluminium is still superior for a given coefficient of dynamic friction. It is in no way surprising or anomalous that half-hard aluminium should show superior deep drawing properties to soft aluminium. The differences in results obtained by Messrs Loxley and Freeman with the three different lubrication conditions must be explained by the variation of coefficient of friction with the various tempers for a given lubricant, but it is misleading to say that the usual superiority of the harder tempers to the softer ones is either anomalous or to be explained wholly as a lubrication effect.

Dr D. Tabor: I was very interested in the whole series of papers which laid so much emphasis on the need for understanding what happens under high pressures to conventional lubricants. I am in full agreement with the importance that Mr Wistreich and others have attached to the effect of high pressures on the rheological properties of lubricants and the consequent probability of having some form of relatively thick film lubrication where one might otherwise expect, at most, a régime of boundary lubrication, or no lubrication at all.

I was very pleased to see the ingenious experimental method adopted by Mr Wistreich to find out how thick the lubricant film was as it went through the die. I am, however, a little worried about it. As I understand it, his model assumes that the lubricant film between the wire and the die is everywhere relatively thick : it is very much thicker in the troughs of the surface asperities, but even at the crests it is several hundred Angstroms thick. On the basis of this assumption he is able to correlate the reduction in electrical resistance between two draws with the amount of soap removed. There are two difficulties here. The first is his deduced specific electrical resistivity of the soap film ; his value of 150 ohms/cm is enormously less than the bulk resistivity of the original soap (10^{10} ohms/cm), and he attributes this to the presence of abraded metal fragments. This is an important deduction, and it would be a great help if Mr Wistreich could collect soap that is squeezed off his wire and measure its electrical resistivity when compressed at pressures comparable with those which operate in the wire-drawing experiment itself. If he obtains a relatively low value, of the same order as 150 ohms/cm, he would have strong direct support for his other conclusions.

The second difficulty is that if this model of thick film lubrication is valid there could be no wear of the die. It may be that in his experiments there was, in fact, no wear. In general, however, there is some wear, and this can only mean that there is some metallic contact or at best a separating film only 1 or 2 mol thick. This does not affect his basic view that the lubrication is primarily due to a thick film of lubricant. This is almost certainly true, but it does affect the deductions made from the electrical resistance measurements. Boundary films have a negligible electrical resistance. Thus a spot only a millionth of an inch in diameter if naked or if covered with a boundary film would have an electrical resistance of the order of 1 ohm. The picture would therefore be that there are hollows containing thick pools of trapped lubricant of high resistance, thinner films over the asperities of intermediate resistance, and at a few points boundary films of very low resistance. All these are in parallel, and the observed resistance would be dominated by the few points where boundary conditions obtain. The change in electrical resistance between the two draws would then correspond primarily to the difference between a small amount of boundary lubrication in the first draw and a slightly greater amount of boundary lubrication in the second. If this is so, his correlation between average film thickness and electrical resistance would have to be seriously modified.

There is one other question I should like to ask. Between the first and second draws in Mr Wistreich's experiments a lubricant film of average thickness about 7000 Å is removed. This is a direct experimental observation which does not depend on the electrical resistance measurements. I wonder whether this quantity bears any relation to the change in surface roughness. The suggestion I am making is that there are relatively thick pools of lubricant stored in the hollows of the surface, and the amount squeezed out corresponds to the average reduction in the height of the surface irregularities. Is there any evidence on this point ?

Mr Wistreich has made a very interesting and stimulating suggestion to account for the very low friction observed in the cigar test compared with the friction observed in direct sliding experiments ; it is an explanation which merits attention and careful consideration. With liquid lubricants a trapped thick film, if it occurred in the cigar test, would certainly be easier to shear than the thin boundary film occurring in ordinary sliding experiments. But with solid lubricants, such as soaps, I doubt whether a large difference would be observed. Our own friction experiments suggest that with good boundary films metallic interaction accounts for very little of the resistance to sliding ; the major part is due to the shearing of the lubricant film itself. If this is so his suggestion amounts to the assumption that the shear strength of a thick film is smaller than that of a thin boundary film. This may be so for liquids, but I doubt whether it would be so for solid lubricants, such as soaps. His assumption may, in due course, turn out to be true, but I have the feeling that we may have to look elsewhere for the explanation of this difference in the coefficients of friction.

While I am here, I should like to make a small correction. In his paper Professor Ford mentioned the important part played by combined normal and tangential stresses in the yielding of friction junctions. He implied that in our work where we had first raised this issue we had only considered this in the elastic range. I think that he must here have misunderstood us. The work we described was largely based on a very elegant experimental study, made by Dr J. S. McFarlane when he was in our laboratory, on the friction and deformation properties of indium. The deformation was completely in the plastic range. He found that under normal loading the local pressures were sufficient to produce plastic flow at the real points of contact. Consequently, the smallest tangential stresses were sufficient to initiate sliding on a microscopic scale. Tangential displacement, however, produced a growth in the area of contact and a corresponding fall in the normal pressure. Consequently, for sliding to proceed the tangential stresses had to be increased until the combined normal and tangential stresses could again produce plastic flow in the enlarged junction. This process could be followed

* Chung, S. Y., and Swift, H. W. *Proc. Instn mech. Engrs*, 1951, **165**, 199–223.

and correlated well with one of the established criteria for plastic flow under combined stresses along the lines indicated by Professor Ford. Unfortunately it does not explain the steady state friction reached in ordinary sliding; this involves a different approach, which is, I think, finding its most promising formulation in some recent work of Mr A. Green of B.I.S.R.A.

P. Spear: I must confess that metal-working lubrication as such is a closed book to me, but unfortunately I have been asked to take an interest in one or two particular problems, and in view of the numerous experts here, I do not see, with your permission, Mr Chairman, why I should not ask a question.

Mr Townend mentions in his paper the method of mechanical de-scaling of rod. I understand this is a relatively new process, and it has been far more developed on the Continent than in the U.K. We are now taking an interest in this process, and the main problem, as Mr Townend states, is that the rod after the mechanical de-scaling is much more difficult to lubricate than rod which has received the normal pickling and liming processes. I appreciate that in mechanical de-scaling the rod goes through the mechanical de-scaling process and then immediately on through the die. There does not appear therefore to be any chance of carrying out any inter-stage operations. Obviously, from a commercial point of view there are very great advantages to be obtained with this method, but from a technical point of view, at the moment, there does appear to be a great deal of difficulty in lubrication. From what can be determined in the published literature, there has been little research work carried out. May I ask whether anyone here has any particular information on this subject?

Dr F. T. Barwell: In reference to Mr Townend's paper, it is not surprising that mechanical de-scaling results in a more difficult surface to lubricate than the one which results from pickling, because the latter process may be expected to leave contaminating films on the surface which may be protective in action. I was interested in Mr Townend's references to lime. The soap provided might be expected to lubricate the metallic surface, but I do find it a little difficult to understand the function of the lime. I would like to ask if he has any real evidence that lime is necessary, or whether it represents traditional practice arising from the use of lime to neutralize residual acids in the pickling processes. It may be possible that works have become accustomed to having lime and regard it as a good thing, without having demonstrated its utility in a rigorous manner.

R. Tourret: I am glad to see the two papers on different aspects of wire-drawing research. As Messrs Ranger and Wistreich says, lubrication in wire-drawing has become the subject of intensive research and development work. No one is too certain which state of lubrication exists in any particular normal application, although Professor Christopherson and his colleagues have demonstrated an elegant method of obtaining the highly desirable state of hydrodynamic lubrication.

We at Thornton Research Centre have carried on a certain amount of research into the state of lubrication existing under ordinary conditions. Our work on die wear using radioactive dies has already been reported.* † It may be of interest if a few details are given of our work on the frictional side.

Our apparatus consisted of a home-made vertical drawbench (Fig A) in which 5-ft lengths of wire could be drawn through a die by weights fastened to their ends. The weights employed were sufficient to accelerate the wire to a final velocity of about 650 ft/min, drawing being at constant acceleration rather than at constant velocity. The passage of the wire through the die was

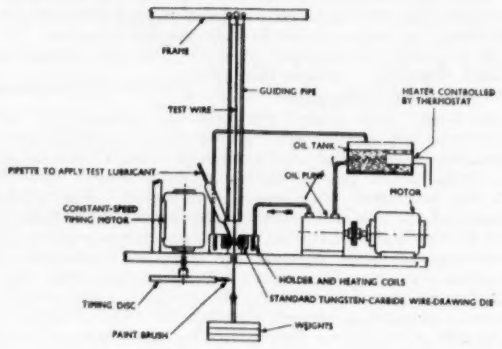


FIG A

SKETCH OF VERTICAL DRAWBENCH

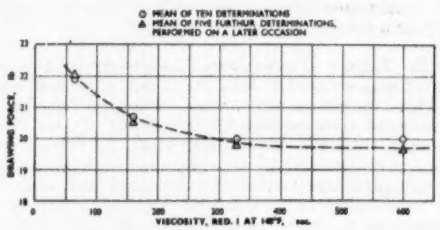

O MEAN OF TEN DETERMINATIONS
Δ MEAN OF FIVE FURTHER DETERMINATIONS, PERFORMED ON A LATER OCCASION
DRAWING FORCE, lb
VISCOSITY, RED. 1 AT 140°F, cs.

FIG B

INFLUENCE OF VISCOSITY OF LUBRICANT ON FORCE REQUIRED TO DRAW ALUMINIUM WIRE ON THE VERTICAL DRAWBENCH, USING STRAIGHT MINERAL OILS

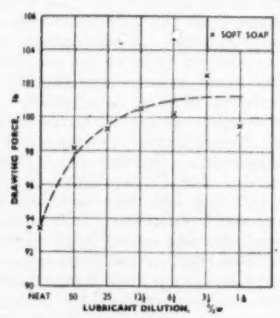


FIG C

EFFECT ON DRAWING FORCE REQUIRED TO DRAW COPPER WIRE THROUGH A TUNGSTEN CARBIDE DIE WHEN USING SOFT SOAP DILUTED TO VARIOUS DEGREES WITH WATER

timed, and from the velocity–time graph the acceleration and hence the drawing force could be calculated.

Some experiments were performed in which aluminium wire was drawn through a steel die lubricated by a series of straight mineral oils of different viscosities refined

* Button, J. C. E., Davies, A. J., and Tourret, R. "A study of tracer methods for assessing the wear of wire-drawing dies." Paper presented at the Radioisotope Techniques Conference, Oxford, July 1951.

† Button, J. C. E., Davies, A. J., and Tourret, R. "Tracer methods for assessing wear of wire-drawing dies," *Nucleonics*, **9** (5), 34.

from the same crude oil by the same process. The results (Fig 2) showed that with a low-viscosity oil a greater drawing force was required than with a high-viscosity oil, indicating that friction was greater with the light oil.

Now, when lubrication is hydrodynamic, the less viscous the fluid, the lower the coefficient of friction and the lower the load that can be carried. On the other hand, with boundary lubrication friction is independent of viscosity. The phenomenon observed of a decrease of friction with increased viscosity was consistent with a state of mixed hydrodynamic–boundary lubrication in which the lighter oils, being more readily displaced from between the rubbing surfaces, allowed a greater proportion of boundary lubrication to occur, resulting in a greater drawing force.

In similar experiments in which copper wire was drawn through a tungsten-carbide die, viscosity had no effect on the drawing force (friction), which indicated that the hydrodynamic component was negligibly small.

Another set of interesting results was obtained when soap solution was used to draw copper wire through a tungsten-carbide die. The results (Fig C) indicated that the drawing force (friction) increased rapidly as the soap was diluted with water. This was consistent with the state of lubrication changing from hydrodynamic or pseudo-hydrodynamic to boundary.

REPLIES TO DISCUSSION

Professor H. Ford: To deal first with the comments on the coefficient of friction, the requirement of brevity in this paper necessarily meant that a lot of detail had to be omitted and that no real explanation of the statements made could be given in the short space. The comment (5) which I added immediately below Table II refers, as I think Dr Butler has already suspected, to the matt and dull appearance of the surface material generally, quite apart from the effect of tiny particles, which appeared to have been torn out of the surface. The general appearance is of a matt surface which almost repeats the surface contour of the strip before rolling, indicating that there is almost a complete protective layer with highly burnished spots at a few places.

Dr Wistreich starts his comments on my paper by suggesting confidently that the lubrication in our compression tests was hydrodynamic, although the speed of relative motion was negligibly small; a little later he suggests that quasi-hydrodynamic conditions may be obtained in cold rolling, where the speeds are much higher. This would seem to be the wrong way round, and it is difficult to envisage any mechanism by which hydrodynamic or quasi-hydrodynamic would exist in the plane compression test. Quasi-hydrodynamic lubrication would seem a difficult term to define, and there may be some difference of meaning attached to it by different people. I suspect it is used to cover a whole number of things, and until we have a better understanding of what is happening at the interface I prefer to avoid terms which merely cover our ignorance.

Professor Christopherson's tests appear to show that hydrodynamic lubrication can be reached by special provisions in wire drawing. This may be; recent experiments with close-clearance shaft-and-cylinder assemblies have shown that exceptional pressures can be established, such as could cause yielding of the softer metals. But it is doubtful if these favourable conditions are reacted in normal cold rolling, and by no stretch of imagination in the plane compression and "cigar" tests. Yet the coefficient of friction is equally low in all these tests. A few recent tests with carefully cleaned and electrolytically polished specimens showed that the coefficient of friction still remained low; and if actual interlocking of the dies and strip were reduced as far as possible by making both very smooth, the coefficient was not much higher than with normal lubricants. The geometrical and stress configurations of the deforming metal must clearly have a large influence on the relative normal and tangential components of stress at the interface between roll or die and the metal. Oxide and other surface films can lower these values still further, but it would not seem necessary to postulate hydrodynamic conditions. I find myself as much "at sea" in Dr Wistreich's pools of lubricant as he does with my own idea; whatever happens to the properties of these lubricants under the extreme pressures involved, I cannot understand how they can offer constraint to the local deformation. Dr Wistreich later says, ". . . these figures tell us that the effect of speed on friction is much the same whatever the roll finish, but the value of μ depends on the roughness of rolls. This is well in accord with the concept of their film lubrication." But surely it is also in accord with boundary lubrication for that matter? The ploughing term is more important in metal working processes than in the slider tests.

The suggestion which I made in my paper was aimed at explaining why friction in plastic deformation processes is generally much lower than that between elastic bodies for otherwise similar conditions. Naturally there are other factors which enter to modify the friction found in any one experiment, but the circumstance that the geometry and configuration of the deforming material is a major factor is clearly demonstrated as between the plane compression test and simple compression of a cylindrical test piece.

Dr Wistreich's experience in the "cigar" test seems to have been different from mine. Recent tests, using carefully cleaned and polished specimens, show only a thin line of matt surface down the middle, the whole of the remaining surface being highly burnished—without lubrication of any form, and with the oxide layer removed and the test performed in a nitrogen atmosphere. These conditions should have given high friction (true boundary friction according to Dr Wistreich's argument) yet the values were not significantly over 0·1.

Mr Butler doubts the statement that "tests with low coefficient of friction leave the strip matt and dull." This is an experimental result and can be confirmed by anybody. He considers that viscosity can modify this conclusion. While it would be unwise to deny this possibility, it is not possible at this stage to say one way or the other because not enough is known about viscosity at these very high pressures: those "lubricants" which we found gave low friction were solids or near solids—and of all of them became solid at high pressure (which is likely), what part does viscosity play?

From the body of tests I have carried out over a number of years it is clear that even with the "best" lubricants and oxide layers, metallic contact still persists, in rolling and plane compression, at discreet spots on the surface. Any pool of liquid trapped between these high regions will be subjected to intense pressure, and no matter how viscous it may become, if one of the metal surfaces is deforming, little resistance could be transmitted through the liquid which would prevent metal—at other discreet points in between the points of contact—being forced up by the indenting effect, so that new points of contact are formed; the readiness with which this could happen depending upon the volume of "pool" remaining the same. In this respect viscosity might help—the speed with which the liquid could force its way into a near-by depression would affect the amount of contact. However, the really low coefficients were obtained with solid lubricants, and other than to say

that the lubricant should be so viscous as to be solid little can be concluded at present.

The detritus observed by Mr Butler seems to be very similar, although a little smaller than the particles we observed.

Professor D. G. Christopherson: I feel I must sound a note of caution about drawing speed. We have only got up to 600 ft/min in our tests, and no doubt many people will regard that as totally inadequate. Moreover, most of our work has been done on copper, which is an easy material to draw. We have not, however, been able to do nearly as much on die wear as we would have liked, and we hope that the results depicted in the paper will be treated only as tentative.

In regard to Dr Cameron's remarks about pressure and temperature effects on viscosity, and the various comments speakers have made about the need for more knowledge of the high pressure properties of lubricants, the lubricants used in our work were chosen solely because they were then among the few for which viscosity measurements at high pressures were available. They were chosen solely because we knew the viscosity at 12 p.s.i., and I dare say it is the first time that any wire drawing lubricant has been selected on that basis.

Dr Cameron referred to the competition between the effect of temperature and the effect of pressure. Whichever of these two effects wins—the effect of pressure in raising the viscosity or the effect of temperature in reducing it—the geometry of the system will influence the extent to which one is able to produce genuine fluid lubrication, and so on. In the particular application which we described we think that the pressure effect wins, though not by an enormously wide margin. We also think the pressures are about twice what they would be if one simply treated the viscosity as constant at atmospheric temperature and pressure. No doubt there would be other cases in which the pressure effect would win much more strongly. There are also other properties of lubricants, *e.g.* thermal properties and specific heat, which we need to know about.

In regard to Dr Tabor's comments on the shear strength of the thicker films, I would say that there must, of course, come a limit to this; it may be that if the film is, say, three, four, or more molecular layers thick, it will be as strong as a single layer and therefore will give the same coefficient of friction. But the number cannot be increased indefinitely, for if there are one hundred molecular layers, one is in effect, dealing with the bulk properties of the fluid, and one is then talking in terms of viscosity, and therefore getting a very much smaller apparent coefficient of friction. I would very much like to have Dr Tabor's opinion of the number of layers, as it were, that are necessary before one can start thinking in terms of a fluid.

Professor Ford remarked about the differences which are observed between the first and the subsequent passes of rolling. Under most conditions there must be a good deal of metallic contact going on at isolated points, but it appears there is a good deal of evidence that leaves an element of what might be called quasi-hydrodynamic lubrication there too, and it does not seem to me that the argument about the first pass and subsequent ones is really relevant one way or the other. After all, when a car is run-in one thinks that the performance is quite different from what it was before, but that is a case where, at any rate, we hope, we are all employing hydrodynamic lubrication.

G. H. Townend: One of the points which has been raised in the discussion is whether the use of a lime coating in wire drawing is any more than a tradition. There is no doubt that it is. The provision of a lime coating improves the lubrication in wire drawing very substantially. There are probably various reasons why this should be so, but the one I would draw attention to as possibly being the most important is the change in rheological properties brought about by adding lime to a soap.

I have measured the pressure required to extrude soap at various rates through a small orifice of known length and cross-section. These measurements have been made at various temperatures. It is found that the pressure required for a given flow is increased by the addition of lime and that the effect is most marked at the high temperature, *e.g.* the pressure required for a given flow rate measured at 1100° C is increased by a factor of about 2 by adding 30 per cent lime to zinc stearate. While these measurements are preliminary ones, they show that the addition of lime makes considerable difference to the resistance flow. I have avoided calling this resistance to flow the viscosity, as soaps and soap–lime mixtures do not behave as Newtonian fluids. Over a certain range of extrusion rates "plug flow" occurs.

On the drawing of mechanically descaled wire, Mr Spear mentioned that wire goes straight into the draw-bench from the descaling machine, and therefore there is no chance of putting on a lime coating as a lime dip. It is normal to use a soap that is a mixture of something like calcium stearate with excess lime, and one might therefore enquire if there is any difference between lime applied by dipping and lime applied as a mixture in the soap. My firm has tried descaling as a separate operation followed by lime dipping. The drawing of lime dipped rod is just as unsatisfactory as normal descaled rod.

Mr Wistreich has commented on my remarks concerning the limitations on drawing speed and on the importance of die life. It is not possible to discuss problems of such importance in a brief reply at anything but a trivial level. However, it may be possible to clear up one or two misunderstandings. When I said that the limitation on drawing speed was more likely to come from the machinery side I did not, of course, mean that it would be impossible to construct machinery for higher speeds but that above a certain speed it would not be economically worthwhile. Further, for the fastener industry this speed will be one at which lubrication presents no serious problem. With regard to die wear, I must assume that Mr Wistriech's remarks are concerned with the production of the types of wire covered by my paper. My remark that die costs were negligible was meant to include the secondary effects such as down-time on a drawing machine due to die changes. Much of the wire for the fastener industry is single-holed, and the time taken to change a single die is very small, since no threading up of a multi-holed machine is involved. Further, the larger sizes of wire coils are not welded together, so that each coil has to be threaded up anyway.

P. Freeman: The points which I shall answer first were made by Dr Jenkin when he referred to Fig 12, p. 306. I agree with him that the ironing operation can be considered analogous to tube drawing, and that the two examples were compared with the object of showing that friction in such an operation may be used advantageously where, for instance, it inhibits the spread of metal over the punch head and, by delaying thinning and subsequent fracture, enables greater reductions to be made. This fact is even more strongly emphasized when differential lubrication is used, *i.e.* when a good lubricant is applied between die and cup, and a poor lubricant between cup and punch. In certain circumstances, with these conditions, still greater reductions can be obtained.

Several interesting points were raised by Mr Barlow concerning the so-called anomolous drawing behaviour of the soft and hard tempers of aluminium which was reported on in the first part of the paper. In deep drawing, fracture of the cup, except in isolated cases,

generally occurs in the region of the blank over the punch head (hemispherical punch) or over the punch profile radius (flat-headed punch). In both cases the material in the zone of fracture is subjected to bi-axial tensile stress conditions. Little is known of the behaviour of metals under such conditions, particularly where a frictional component is also operative, as is the case in deep drawing. It is observed, however, that the position of the fracture relative to the punch head and presumably the stress conditions at fracture are affected by friction and that the higher the effective coefficient of friction over the punch head, the closer the approach of the zone of failure is to the cylindrical walls. To attribute the aluminium anomaly with the flat-headed punch entirely to the stress–strain strength properties of the hard and soft tempers could, it seems, be justified only were failure to occur in the parallel walls of the cup.

J. G. Wistreich: Professor Thompson, intrigued by the appearance of the electric resistance traces in the paper by Ranger and myself, doubts whether the explanation advanced by us is sufficient. Whilst I, too, am drawn to the idea of continual breakdown and re-formation of the film, I do not see why this should induce any more regularity of electrical resistance variations than the surface imperfections mentioned by us. I fear that Ranger and I have perhaps misled him by the use of the term "oscillation"; "variation" is undoubtedly a more apt description of our observations, and I can assure Professor Thompson that our resistance patterns were neither regular nor periodic. I should also hesitate to link these patterns with the friction patterns recorded by MacFarlane and Wilson. The latter are oscillatory in the strict sense of the word, and the mechanism responsible for the oscillation is, of course, well understood.

As for Dr Tabor's penetrating comments, I should like to defer our reply in order to do them full justice. There are, however, two matters relating to fact which I can answer now. First, in the experiment in question we used wax, we coated the wire very heavily, and the amount of wire drawn was small; judging from general experience, I should say that the lubrication was very good and the rate of die wear must have been very small. Second, as far as we could tell, the surface roughness was not changed significantly by the test pass. I fully share Dr Tabor's cautious attitude to our estimates of resistivity, and I have made a note of his suggestion for a check measurement. At the same time I would remind him that both wax and soap collected off the wire was usually magnetic and—as mentioned—we found that the wire stretched in tension, instead of being drawn, was covered with a small amount of metallic dust. This has puzzled us greatly, and we have wondered whether it has been encountered before in tensile tests of metals in a form other than wire.

Mr Tourret has criticized my earlier remarks about hydrodynamic lubrication. I do not see any contradiction between these remarks and his graph of drawing force against viscosity: surely, the Stribeck curve has two branches with a minimum in between, and it is the left-hand branch which is appropriate to the régime of lubrication, which, it has been suggested by several speakers, is prevalent in metal working; on this branch of the curve lowering the viscosity of the lubricant causes the friction to increase.

May I now endorse and, if possible, strengthen Mr Townend's remarks in reply to Dr Barwell's question about lime. The wire industry strongly dislikes lime and has tried hard to get rid of it. Borax and many other substances have been tried, but, by and large, lime is more effective and, of course, by far the cheapest coating. Dr Barwell is probably right in his surmise that initially lime was introduced as a neutralizer of traces of acid, but at the same time there is no doubt about its merits in improving lubrication. Its function is still obscure, but two significant facts about lime are that: (1) contamination by calcium carbonate is deleterious, and (2) the smaller the particle size the better the lime.

In this connexion I was most interested in Mr Townend's account of his extrusion experiments. This may well point a way to a better understanding of how lime improves solid lubrication in drawing.

A. E. Ranger: Mr Wistreich has replied briefly to Dr Tabor's comments on our paper, but I feel that some further amplification is desirable. Dr Tabor suggests that, in the experiment to measure film thickness, the wax removed by the second die was squeezed out from the hollows of the wire surface. If wire is drawn through several dies in succession without relubrication the hollows eventually close up, giving a burnished appearance to the wire. That this was not in fact the case in our experiment was mentioned in the paper (p. 312). The wire surface was subjected to microscopic examination both before and after drawing through the second die, and the change in shape of the hollows was consistent with normal deformation.

Secondly, Dr Tabor assumes that our picture of lubrication implies that die and wire are never in intimate contact. If we have given this impression, then the fault is ours, but it was certainly not intended. The oscillograph traces show that the film resistance periodically falls to "zero." The traces in Fig 4 (*b*) of Professor Christopherson's paper also demonstrate this particular point. Our interpretation is that these instances of zero resistance indicate intimate contact between the two components, but at other times the wire and die are completely separated by a film, the thickness of which is everywhere greater than molecular dimensions.

Since preparing this paper we have investigated further the production of metallic dust on the surface of the wire when stretched in tension. A length of the wire was polished by a chemical method * and stretched. No dust was formed in this case. It therefore appears that the phenomenon is associated with the method of production of the wire and not with the metal itself.

J. C. Wistreich: The points raised by other speakers, including Professor Thompson in his opening review of the papers, have already, it is hoped, been adequately dealt with during the discussion. It is gratifying to note that our view that lubrication in wire drawing and probably in the majority of metal-working processes is not of the pure boundary type, has received support from so many sides, and Dr Cameron's comments on the similarity of frictional phenomena of gears and metal working have been noted with keen interest. It is hoped that his contribution may lead to fruitful cross fertilization between two difficult fields of the science of lubrication.

A. L. H. Perry: Dr Jenkin referred to various points which were not, in his opinion, quite exact, and, in view of his unique position with Tube Investments Ltd., I accept his corrections unreservedly.

I was interested in his reference to atmospheric conditions as playing a part. I did some work, many years ago, on the drawing of pure nickel tubes, and I concluded that the best lubricant was dry soap powder. On damp days, however, it was necessary to dry the soap powder frequently, otherwise the tubes soon became scored. Turning now to the question of tube drawing lubrication in general, I indicated in my paper the difficulties that my firm, as suppliers, experience with lubricants for this particular operation, and how it is all tied up with this curious region of lubrication which, for

* Marshall, W. A. *Research*, 1954, **7**, 89.

want of a better term, is called quasi-hydrodynamic. This is probably the most baffling and unmanageable region that suppliers of lubricants have to deal with nowadays, therefore all the attention that has been focused on it at this meeting is very interesting to me, and I hope that it will produce results. In spite of a considerable amount of research, the industry still lacks the ideal metal-working lubricant that modern production developments demand.

Dr Jenkin also referred to staining in the annealing process. As he says, that is another point that has hardly been referred to at this meeting, and yet this is a problem that gives my firm some of its most severe and unremitting headaches; it has nothing directly to do, of course, with the deformation processes which have occupied us here today, but in practice it often greatly influences the choice of lubricants for these processes.

J. S. MacFarlane and A. J. Wilson: In reply to the specific points raised by Professor Thompson, we certainly agree that the conclusions we draw from Fig 5, p. 330, are in some degree hypothetical. Our justification is that it serves to illustrate how a marginal improvement in lubrication may sometimes enable a large economy in production costs to be made. Professor Thompson's mention of the possible detrimental effects of overworking of the surface through inadequate lubrication is interesting. Where the metal is used in the hard-drawn condition it is possible that corrosion resistance as well as fatigue strength would be diminished.

The use of glass as a lubricant in high-temperature extrusion is of great promise. It would be particularly interesting to know whether the lubrication is purely hydrodynamic or whether the metal surface is protected by a chemical reaction. Perhaps, however, it would be unwise to expect major contributions from the oil industry to this field of knowledge.

The figures quoted in Professor Thompson's summary from Table I, p. 327, are misleading. The reduction in coefficient of friction brought about by increased time of exposure is, though large, not quite so large as is there suggested. Reference to the table shows that for the particular instance quoted (Oil A at 180° C) the drop is from 1·50 to 0·55.

Turning now to the interesting points raised by Dr Jenkin, we must first agree with him that friction is not all important. We do not dispute his assertion that the prime function of the lubricant is to enable high reductions to be achieved; however, it is difficult to see how it can do this other than by reducing the friction, either hydrodynamically or by a boundary mechanism. Though the question of the friction coefficient may not be all important, it is certainly much vexed, and it was, perhaps, the first of our objects to try to discover just how intimately the boundary lubricating properties of an oil are related to its drawing properties. For a long time much play has been made with friction coefficients, and we thought it might be useful to investigate the degree of their importance. Such paradoxes as that mentioned by Dr Jenkin, that a lubricant giving a high coefficient of friction sometimes produces the more satisfactory results, surely deserve investigation.

We agree with Dr Jenkin that it is doubtful whether copper sliding on copper can be regarded as simulating drawbench conditions. However, it does serve as a sensitive method of distinguishing between the lubricating properties of various oil blends. Experiments with tungsten carbide sliding on copper appear at first sight to be more relevant, but here serious uncertainties are introduced by the unknown and uncontrollable amount of pick-up. We thought that to take the extremes of copper and clean tungsten carbide on copper would be more informative than to use surfaces mutually contaminated to an arbitrary extent.

Dr Jenkin reminds us of the factors that we have neglected. We sin no less than others in this respect, but no doubt he will agree that to attempt to control them all at the outset of an exploratory investigation, such as ours, would be a labour at which Hercules might have misgivings.

Finally, we apologize to Mr Wistreich for interpreting his expression "high stress concentrations" too literally in regard to die-ringing. Nevertheless, we incline to the view that increased friction, though it may induce a reduction in die pressure, will nevertheless lead to a more severe combination of normal and tangential stress in the surface of the die, and hence contribute to its early failure.

Dr C. B. Davies: I am sure that we can safely conclude that the impressive, varied, and versatile schools of thought on metal working represented here this afternoon and this evening have been stimulated in such a way that progress in this important subject will be accelerated.

I have felt the challenge of the large amount of work to be done not only from the fundamental point of view, but also from an applicational or practical one—namely, getting significant test procedures, and I feel we have all had this emphasis on performance brought to our notice. It is so easy to adopt and use performance tests which, even if they are statistically significant, may, through having artificial conditions or some laboratory flavour about them, distort the picture with regard to what is actually happening in the field, and I think all of us have agreed that the pitfall of the non-significant laboratory test must be avoided at all costs. However, often these laboratory tests, even if they do not fulfil the optimistic aim that some people have for them, are of the greatest importance in learning some things pertaining to the fundamentals of the processes we study; not fundamental in the way that Dr Bowden's school deals with them, but perhaps a half-way house between the knowledge obtainable from performance tests proper and the basic work which has been so ably put before us by our academic friends today.

Finally, I would like to express thanks to Dr Galloway and Professor Thompson for their guidance in these sessions. We are most grateful to them, and I would like to thank the authors and the contributors to the discussion. Particularly on a personal note, I feel I was given too much credit for the organization, and therefore I would like to express grateful appreciation to Mr George Sell, of the Institute of Petroleum, and to Mr Tourret, now of the Admiralty Oil Laboratory, for their assistance.

Dr E. B. Evans: Dr Davies has thanked the authors and the rapporteurs for their very excellent work and the efforts they have made in the preparation and presentation of these papers. Quite a lot of work is involved in preparing a paper for discussion at a meeting such as this, and we are all very grateful, as Dr Davies said, to the authors. But quite a lot of work is also involved, and quite a lot of thought, too, in the organization of a meeting and in the collection and arrangement of the papers, and for that we do, in spite of his modest disclaimer, owe Dr Davies a great deal of gratitude. I am sure you will all join with me in thanking Dr Davies for his work in organizing this Symposium, and I think we should also associate Mr Tourret's name with that of Dr Davies. We also appreciate the delightful way in which Dr Davies, as Chairman, has conducted this meeting.

We should also thank the Institute of Electrical Engineers for letting us have the use of their hall—the meeting is a little larger than we can accommodate at the Institute of Petroleum.

WRITTEN DISCUSSION

J. G. Wistreich: There are a few weak links in the argument adduced by Professor Christopherson and his colleagues in support of their claim for the attainment of hydrodynamic lubrications in wire drawing, which unnecessarily detract from their otherwise well-founded conclusions. It is not correct to say that "in the absence of any friction (the drawing force) is equal to the work done per unit length in pulling out a tensile specimen to the same reduction of area in a tension machine." In point of fact, the former is always greater than the latter, because of the inhomogeneity of deformation in the die. The inequality is appreciable if the area of contact between wire and die is small in relation to the cross-sectional area of the wire, and vice versa. In the absence of information about die configuration in the authors' experiments it is impossible to say whether they were right to neglect this inequality or not. Moreover, as shown in Fig 8 of the paper, the deformation was less inhomogeneous with forced lubrication than without, so that the frictionless component of the drawing force in Fig 2 (*a*) was probably less than in Fig 2 (*b*). The justification for marking the intervals "IDF + Drag" in Fig 2 (*a*) and "IDF" in Fig 2 (*b*) is further weakened by the authors' remarks concerning the influence of strain rate on the strength of metals: what data did the authors use to arrive at their estimate of the "dynamic" strength? In my opinion, published data on the effect of strain rate are not sufficiently complete to make an estimate of it. The real value of Fig 2 (*a*) is to be found in the fact that during starting and stopping the drawing force was substantially larger than at full speed, even though at full speed the frictional drag in the tube must have been much larger than during the starting and stopping.

I also disagree with the authors' interpretation of their Fig 8. Several investigators have studied the distortion of a grid scribed on a diametral wire, but evidence published so far does not justify the authors' statement that "the greater the coefficient of friction, the greater the distortion of the wire." Indeed, I would suggest that the observations recorded in Fig 8 are probably the outcome of back-pull and radial compression by the oil ahead of the die, and not of reduced friction in the die.

Finally, I should like to ask the authors what further proof is needed to satisfy them that "the mechanism of wear in tungsten carbide is the same as in steel." Surely Bowden and Tabor and their co-workers have amassed enough evidence by now to show that the basic mechanism is the same not only in metals but also in non-metals, such as diamond. As for the characteristic manner of wear of wire drawing dies, which the authors summarize in their introduction, this is the same in all dies, whether made of steel, sintered carbide, or diamond; the difference between the materials manifests itself only in the rate of wear.

Mr Townend has skilfully summarized dry drawing practice and the problems arising from the mechanical de-scaling of rod. He aptly stresses that, in the circumstances, it is suprising that wire drawing works so well. However, I would not agree with him that machinery is the cause of limitation of wire drawing speeds. On the contrary, difficulties of lubrication are, at present, the principal limitation. This is particularly true of dry drawing, where, presumably, owing to difficulties of heat removal all known lubricants break down above a critical speed, the magnitude of which depends on the hardness and size of the wire. The method of lubrication outlined by Professor Christopherson and his colleagues seems to offer a possible solution of this difficulty. Mr Townend's argument about die life misses the point: he is, of course, right in dismissing the cost of dies, but surely die performance is a serious problem, because most wire drawing machines must be stopped for replacement of worn dies. Some time ago I was given statistics of a wire mill, which indicated that the time lost by replacement of worn dies was equivalent to one machine in twenty standing permanently idle. The cost of this idle machine and of the space it occupies, and the cost of labour engaged in die replacement, are the real reasons why die life needs to be improved.

Messrs. MacFarlane and Wilson, in referring to my interpretation of the causes of ringing, suggest that high stress concentration at the entry of the tube into the die will be reduced by improved lubrication. This is not so; on the contrary, as friction is lowered the die pressure increases. MacLellan * drew attention to this in a theoretical analysis of wire drawing, and I have recently confirmed this experimentally.† Naturally, improved lubrication may nevertheless reduce the severity of ringing by virtue of the better protection of the die surface.

R. B. Sims: Professor F. C. Thompson has indicated that in some metal-working processes the speed of rubbing between the tools and workpiece might be limited by the fact that the amount of heat liberated could break down the lubricant film between them. At speeds reached in mills (over 5000 f.p.m. have been used in 5-stand tandem mills) this does not seem to be the case; indeed, in tinplate rolling, a reduction in thickness is possible at slow speeds only when very high tensions are put on the strip. In rolling at least, therefore, the higher the speed, the easier the metals are to deform. Moreover, the account given of the effect of friction in rolling was intended only to acquaint readers, not familiar with the rolling process, of the particular importance of friction in cold rolling. As Professor Thompson has pointed out, it is only a summary of the literature which has appeared on this topic.

Dealing with Professor Thompson's last point, application of the Christopherson "pump" to rolling, it is unlikely that this will be a commercial development for many years to come. As Dr Cameron has indicated, the funnel would quickly become filled with the detritus which is produced in rolling. It would also become clogged with the heavy greases which are always present in a rolling mill, and in the event of a cobble or strip breakage at speed the whole device would be wrecked.

It is interesting to read that Dr Cameron has found coefficients of friction comparable to those found by Arthur and myself in his experiments on gear teeth. When these values were first measured it was thought that the experimental technique was incorrect, because such low values of friction had not been published hitherto. After careful checking of the technique the conclusion was reached that low values of friction were found in rolling because relatively thick films of lubricant could be sustained in processes where the flow pattern could be considered as two-dimensional. In the Bowden and Tabor experiments the sliding of the hemisphere over a flat surface can push aside the relatively thick films of lubricant, leaving the slider to be separated from the flat surface only by layers of lubricant chemically bonded to the surface.

In the rolling process, where the strip is very wide in the lateral direction, and similarly in the case of gear teeth, the lubricant cannot be pushed sideways away from the contacting areas except at the edges, and

* MacLellan, G. D. S. *J. Iron St. Inst.*, 1952, **81**, 1. † To be published.

therefore it seems possible that once relatively thick films have been deposited on the surface, they can be maintained by the geometry of the process.

The results published by Professor Ford show a correlation between surface lubricity, and the coefficient of friction between the rolls and the material may have misled Mr Butler into assuming that his results can be compared directly with rolling. The surface quality of strip produced in rolling has no direct relationship to the coefficient of friction, but is essentially a function of the rolling conditions in a particular mill. For example, in tinplate rolling the coefficient of friction is probably between 0·08 and 0·06 when the strip is being threaded through the mill at a speed of perhaps 50 f.p.m. in the first stand and 200 f.p.m. in the last stand, and μ falls to as low as 0·03 to 0·04 in the last stand when the strip is at the full production speed of over 3000 f.p.m. Despite these very low coefficients of friction, the strip leaving the last stand of a tandem tinplate mill has a very high lustre indeed.

The fact that the surface of the strip rolled by Professor Ford with low coefficients of friction was badly torn is indicative of the fact that the planishing action so essential to the high polish found in cold rolled strip no longer occurred. It can be produced quite easily in strip by varying the rolling conditions.

In commenting on the conclusions reached in the paper, Mr Wistreich does not appear to have given consideration to the conditions under which the experiments were made. I should like to summarize these again, even at the risk of repetition. Referring to Fig 4, the conditions of the experiments were :

Curve	Conditions	Purpose of experiment
D	Strip rolled with soluble oil emulsion (1 : 10 oil–water ratio) sprayed on both sides and rolls at rate of 10 g.p.m.	Normal rolling conditions.
A	Strip immersed in sample of emulsion, washed in running water and dried before rolling. Rolls clean and dry.	No liquid present. Only solid deposit from the oil remaining on strip surface.
B	As for A, but swabbed in benzine after washing and dried before rolling. Rolls clean and dry.	Thinner solid layer present than at A.
C	As for A, but swabbed lightly in benzine and MgO, and then washed and dried. Note that MgO was not present in quantity as a lubricant.	Very thin solid layer of lubricant present.

Now from these results the following observations were made. From curves D and A the presence of a "liquid" film is clearly unnecessary for speed effect. From A and B the speed effect is terminated at a lower speed with a solid lubricant layer, and from A, B, and C it is clear that within a solid film of sufficient thickness the speed effect may be eliminated.

These are observations, and in experimental work producing results of any significance the experimenter expects, and indeed is expected, to draw conclusions, which may even be speculative, providing speculation is not concealed by a cloak of assertion. The first of the conclusions made in the paper was that the present experiments confirmed the earlier observations of Sims and Arthur that the speed effect was a frictional phenomenon. The second was that the magnitude of the speed effect depended on the thickness of the lubricant film, and, although this was not stated explicitly, the effect clearly depends on the viscosity of the layer, since no speed effect was observed in earlier work with quite thick layers of graphite, talc, and vermiculite used as lubricants.

Occam, perhaps, would not apply his razor unkindly to speculation on the mechanism whereby a demonstably solid layer, thin enough not to be visible, should vary in thickness when the speed of rolling is increased. Clearly, a thicker layer than that already present could not be drawn into the rolls, since a reservoir of mobile lubricant was not available. The suggestion was made that the solid layer is "extruded" (unfortunately a term used loosely) off the strip. This mechanism then links the rheological properties of the layer with speed in a manner which fits he facts, and the observations of Claypoole and others. It also gives a lead for the construction of oils suitable to industrial rolling.

Turning to the remainder of the points made by Mr Wistreich, the ratio $\mu_{53}/\mu_{294} = 0{\cdot}68$ may easily be fortuitous, as Sims and Arthur indicated. The experiments were made at different times with different samples of oil, and although the broad facts which emerge from the experiment are valid—that a smoother roll given a lower value of μ at lower speeds—the data are not suitable to derive a detailed comparison, particularly when they involve the comparison of small quantities. Mr Wistreich, moreover, fails to indicate the significance of his figures, and none seems obvious.

The speed effect is exhibited under a well defined set of conditions, as Ford and others have shown. Mr Wistreich will find, doubtlessly, that when he is able to arrange his experimental mill to roll under loads which contain a large frictional component, his observations will be in agreement with those of industry. There are no grounds, incidentally, in assigning a significant rôle to the elastic deformations in the rolls in producing hydrodynamic films.

In commenting on the commercial aspects of the problem Mr Wistreich should not minimize the speed effect in industry. Scrap due to it is rarely less than 2 per cent of the total output, and usually between 4 and 6 per cent. Bearing in mind the millions of tons of highly priced metal which is rolled today, it is clear that the cold rolling industry would pay a premium for a lubricant which suppressed the effect without detriment to the other desirable rolling properties, regardless of whether it was claimed to have better lubricity or even if it had extra crystallizing additions.

Returning to Occam for the moment, Mr Wistreich would do well not to place too much stress on the nomenclature to be applied to the phenomenon under discussion. It is now generally agreed that in metal working, and in many forms of lubrication where the rubbing surfaces come closely to a two-dimensional pattern, that thicker films and lower frictional coefficients are found than those given by Bowden and Tabor and their school for similar materials and lubricants. It is impossible to say whether this is due to a purely viscous phenomenon, designated as "hydrodynamic" lubrication by Osborn Reynolds and others, or whether it is a chemical process more closely related to the true "boundary" lubrication investigated in detail by Bowden and Tabor. A decision on the point may come when a mathematical analysis is obtained which fits satisfactorily the observed facts. Until more work has been done to establish a basis for classification it would be better to leave the matter open.

The need for consistent and reproducible frictional conditions is vital to two basic British industries—metal forming, and, as Dr Cameron has stated, engineering. A solution would be welcomed whether it be boundary or hydrodynamic in character.

THE

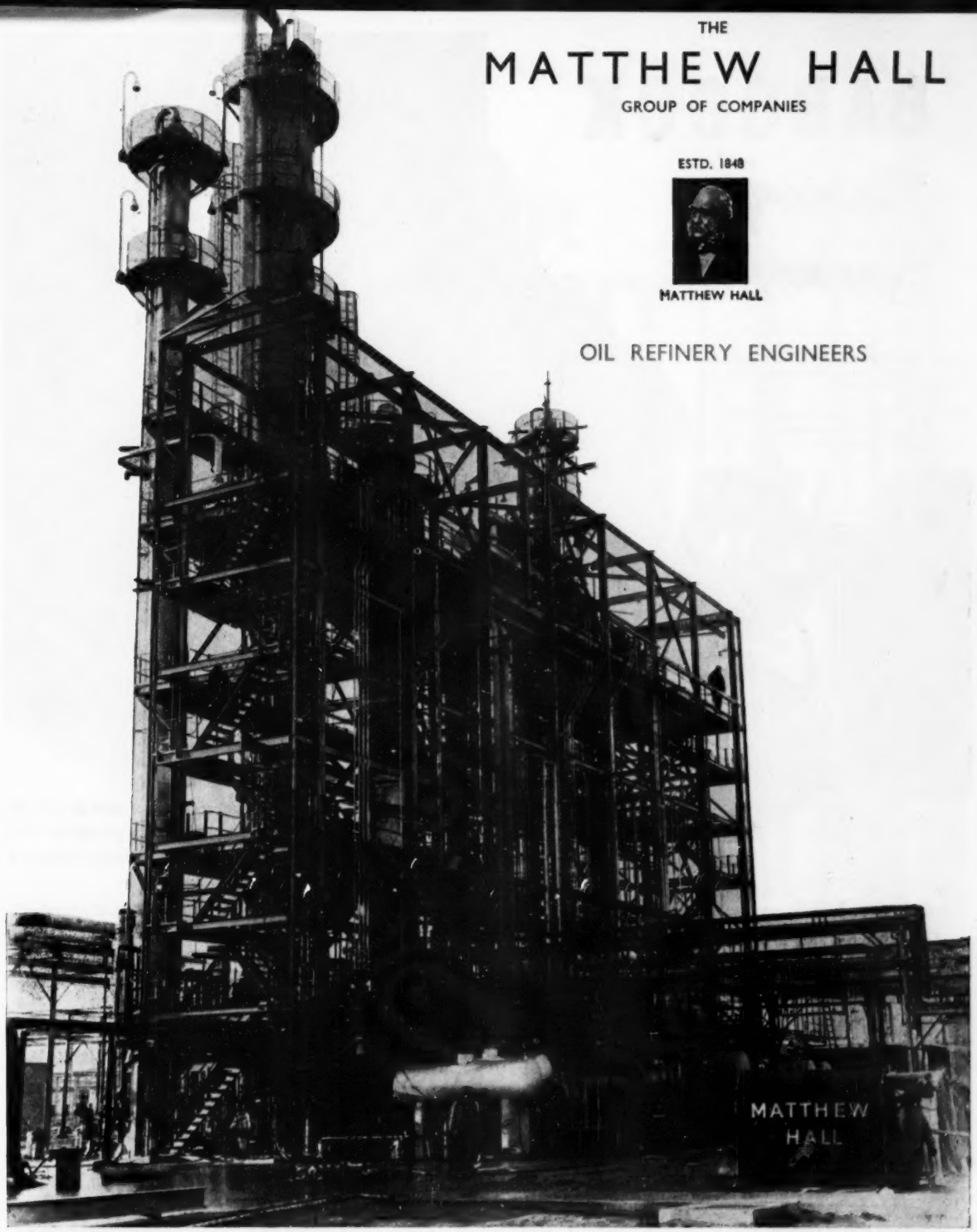
MATTHEW HALL

GROUP OF COMPANIES

ESTD. 1848

MATTHEW HALL

OIL REFINERY ENGINEERS



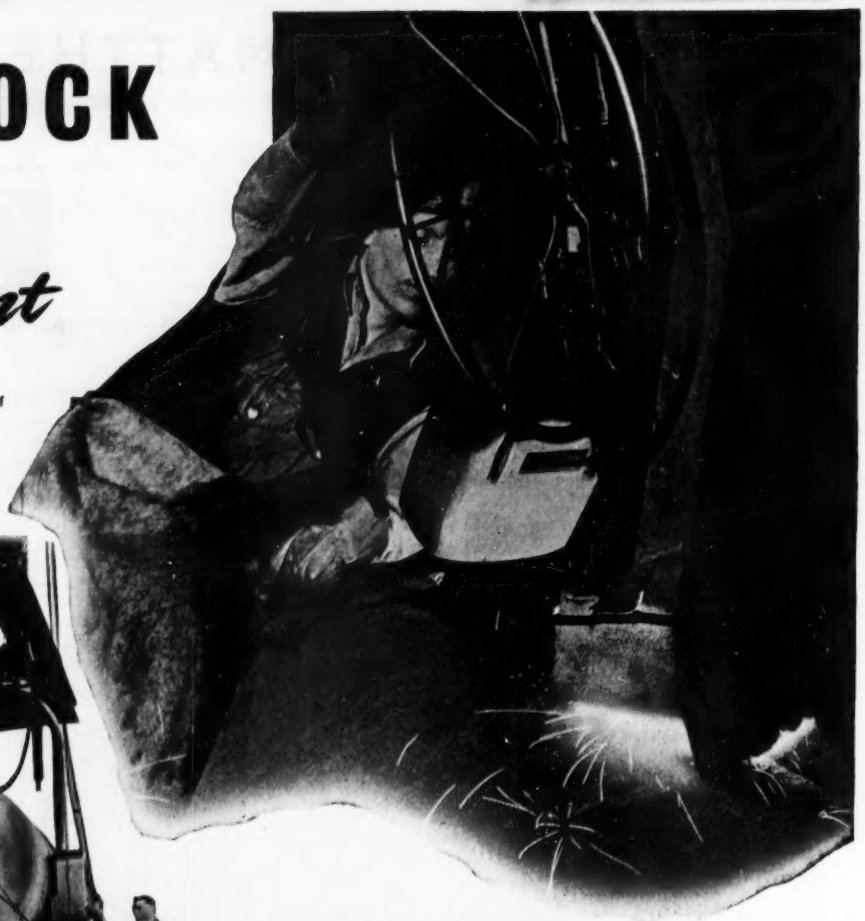
THE MATTHEW HALL GROUP OF COMPANIES

MATTHEW HALL & CO., LTD. MATTHEW HALL (PTY.) LTD.
KELCO (METALS) LTD. GARCHEY LTD.

LONDON	Dorset Square, N.W.1	JOHANNESBURG	52, Commissioner Street	BELFAST	Greenwood Avenue
MANCHESTER	14, Lloyd Street	GERMISTON	Wadeville	DUBLIN	29, Westland Row
GLASGOW	Dykehead Street, E.2	DURBAN	100-102, Williams Road	WEST INDIES	Kingston, Jamaica
BRISTOL	St. Stephen's Street	CAPE TOWN	Epping Industrial Estate	BULAWAYO	Ironbridge Road
		WELKOM	Third Street		

BABCOCK

Refinery Equipment



Right: Fusion-welding the longitudinal seam of a pressure vessel at the Renfrew works of Babcock & Wilcox, Ltd.

Below: Routine X-ray examination, applied to every inch of weld, shows less than 10 inches defective in every *mile*.

BOILERS

WELDED PRESSURE VESSELS

HEAT EXCHANGERS

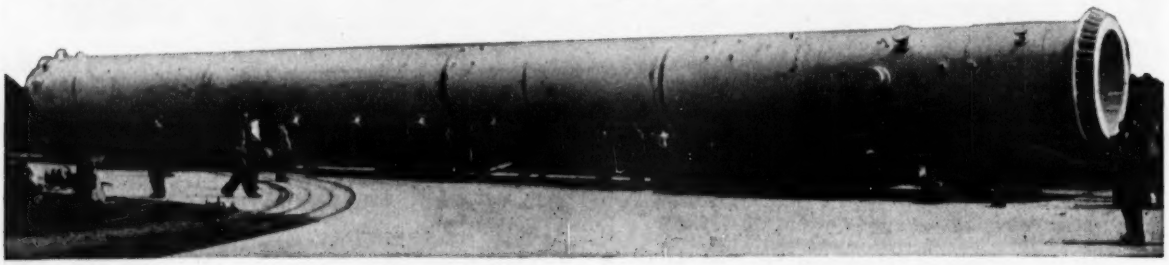
WASTE-HEAT UTILIZATION PLANT

CRANES

The picture above symbolises an experience of over 20 years in the manufacture of fusion-welded pressure vessels, a process that was pioneered by Babcock & Wilcox and developed by them to its present state of perfection.

The operator is supervising the automatic welding of a longitudinal seam in a large pressure vessel—maybe the high-pressure drum of a Babcock boiler, a high-pressure manifold or part of a large treating tower destined for one of the world's new oil refineries, many of which have Babcock equipment.

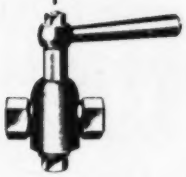
With 75 years of boilermaking experience, including their 23 years development of the fusion-welding process for the manufacture of pressure vessels, Babcock & Wilcox are outstandingly well equipped to meet the demands of the oil industry for complete modern steam-raising plants, treating towers, high-pressure manifolds, heat exchangers and plant for the utilization of waste heat.



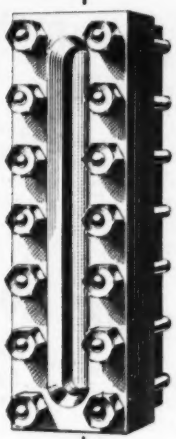
BABCOCK & WILCOX LTD · BABCOCK HOUSE · FARRINGDON STREET · LONDON · E.C.4

Klingerise **YOUR PLANT**

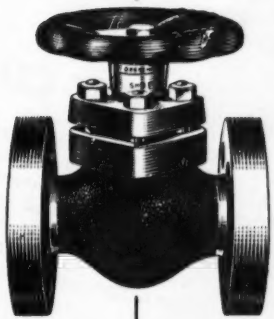
COCKS



GAUGES



VALVES



INSTALL *Klinger* **FITTINGS**

Write for the Klinger Master Catalogue which describes the complete range of Klinger products, compressed asbestos jointings for all purposes, valves, cocks, level gauges, synthetic and silicone rubbers.

RICHARD KLINGER LIMITED, KLINGERIT WORKS, SIDCUP, KENT, ENGLAND

Manufacturing Licensees for Canada — Agents throughout the World — Manufacturing Licensees for U.S.A.

JOSEPH ROBB & COMPANY, LIMITED
5575, COTE ST. PAUL ROAD, MONTREAL, 20, CANADA
Telephone: WILBANK 3181 Cable: ROBCO
Branches at: SYDNEY, N.S., HALIFAX, N.S., OTTAWA, Ont., TORONTO, Ont., HAMILTON, Ont., WINNIPEG, Man., EDMONTON, Alta., VANCOUVER, B.C.

THE KLINGER CORPORATION OF AMERICA
95, RIVER STREET, HOBOKEN, NEW JERSEY, U.S.A.
Telephone: HOBOKEN 2-7915 Cable: KLINGDALE
New York
Telephone: WHITEHALL 3-8996

DURAX

THE INDISPENSABLE REFRACTORY!

- ★ RAMMING PATCHING & MONOLITHIC LININGS
- ★ SPECIAL & EMERGENCY SHAPES · COMPLETE LININGS
- ★ THIN SOUND & STRONG JOINTING
- ★ PNEUMATIC GUN CEMENT LININGS

DURAX No 1

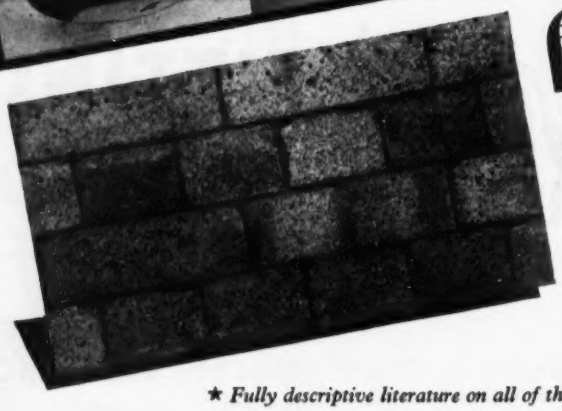
PLASTIC FIREBRICK COMPOSITION

Supplied ready mixed for immediate use. Suitable for rammed linings and patching existing Durax No. 1 or firebrick linings. Service temperature range 1300/1650°C.

DURAX No 2

REFRACTORY CONCRETE

For casting in situ and making special shapes. Supplied dry. Special characteristics include—rapid setting as hard as firebrick: pours into position: no permanent volume change: little tendency to spall. Maximum service temperature 1300°C.



DURAX No 3

REFRACTORY CEMENT

A finely ground air setting cement for jointing all types of firebricks. Supplied dry. Special characteristics include—produces thin and strong joints: negligible shrinkage: highly refractory: economical in use. Maximum service temperature 1650°C.

DURAX No 5

GUNNING OR PLASTERING CEMENT

A cement designed for application with a pneumatic gun. Alternatively it may be plastered into position. Durax No. 5 has little rebound loss when applied by gun to Catalytic Regenerators and forms a dense tough lining with a maximum service temperature of 1300°C.

★ *Fully descriptive literature on all of these grades of Durax is available on request*

GENERAL REFRACTORIES LTD

GENEFAX HOUSE · SHEFFIELD 10 Telephone SHEFFIELD 31113

284

ENGLISH DRILLING EQUIPMENT CO LTD

BILBAO HOUSE, 36–38 NEW BROAD STREET, LONDON, E.C.2

Telephone: LONdon Wall 4941–4 **Telegrams: Bullwheel, Ave, London**

EDECO

REGD. TRADE MARK

The Edeco Twin Jet Bit is recommended for use in conjunction with high velocity drilling fluid circulation. The cuttings are swept upwards by the jet stream, keeping the bottom of the hole clean, allowing FASTER PENETRATION and MORE HOLE per bit.

The Edeco Twin Jet Bits are available with all the cutter designs illustrated in the EDECO Rock Bit Catalogue No. 82.

The Jet Circulation ways are orged into the body of the bit avoiding the necessity for separate Tubes and allowing thicker walls around the circulation passages and, consequently, less danger of "cut outs".

The outlets of these passages are fitted with Tungsten Carbide Nozzles with bore size to suit customer's requirements.

TWIN JET

TYPE VS

SUBSIDIARY COMPANIES

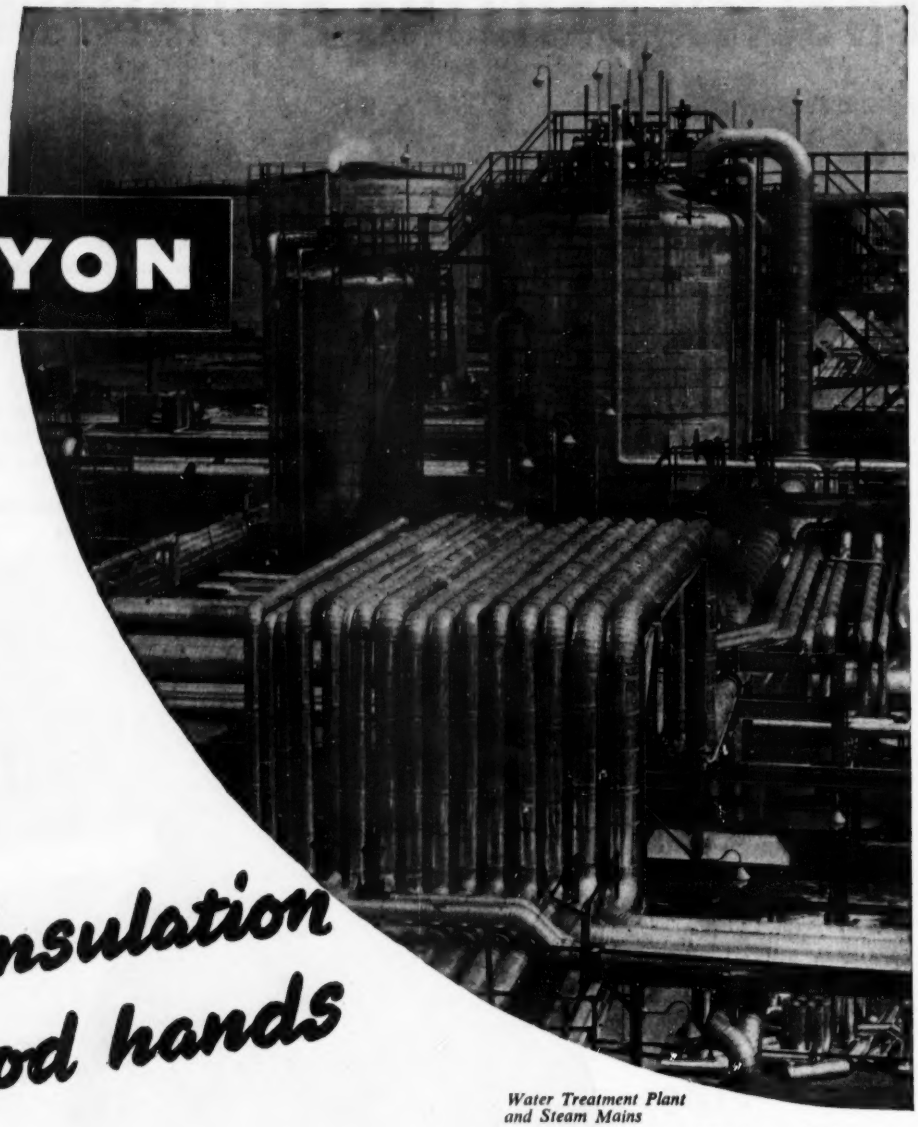
EDECO PROSPECTORS LTD
Barlby Works, Lindley Moor Road,
Nr. Huddersfield, Yorks.
Telephone: Elland 2876/7

EDECO CANADA LTD
10103–80th Avenue,
Edmonton, Alberta.
Telephone: Edmonton 35825

EDECO GERMANY G.M.B.H.
Folschblock C, Hermannstr. 40,
Hamburg, 1.
Telephone: Hamburg 33 39 67

EDECO (TRINIDAD) LTD
P.O. Box 27, San Fernando,
Trinidad, B.W.I.
Telephone: San Fernando 2819

KENYON



Heat Insulation - in good hands

Water Treatment Plant and Steam Mains

Photograph by courtesy of The Vacuum Oil Company, Coryton Refinery

Kenyon provide a complete thermal insulation service to the oil industry, including technical advice on thermal insulation specifications, and finishes for all conditions. Supply of materials, application, supervision, on sites throughout the world.

A world of experience

WILLIAM KENYON & SONS LTD · DUKINFIELD · CHESHIRE

No.KH.160

B.T.L. INSTRUMENT INFORMATION

ELECTROMETRIC TITRIMETER FOR DETERMINATION OF BROMINE NUMBER TO IP. 130/53

The thirteenth edition of the Institute of Petroleum "Standard Methods for Testing Petroleum and its Products (1953)" under I.P. 130/53 calls for an electrometric titrimeter for the determination of the bromine number of gasoline, kerosine and distillates in the gas-oil boiling range. The B.T.L. Electrometric Titrimeter, comprising a titration stand and end-point indicator, has been designed for this purpose.

The titration stand consists of a glass titration vessel to the specified dimensions, a 50 ml. burette with bent delivery jet, a motor driven stirrer with glass paddle, and two platinum electrodes. These are all supported on a retort stand with two retort rods and the necessary clamps and bossheads.

The end-point indicator has a circuit of the 'dead-stop' type and the equipment is built into a portable metal case on the sloping front panel of which are mounted the cathode ray indicator tube, potentiometer and rheostat for regulating stirrer speed. A mains switch and pilot light are also incorporated. On the back of the case are plugs and sockets for connection to the mains and to the stirrer motor, terminals for connection to the electrodes and a fuse.

The instrument is suitable for use on 100/110v, 200/220v, and 230/250, A.C. ONLY.

Full details are provided in Technical Leaflet No. T50 available on request

BTL

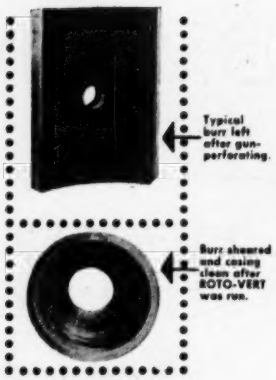
Member of SCIEX

BAIRD & TATLOCK

(LONDON) LTD.

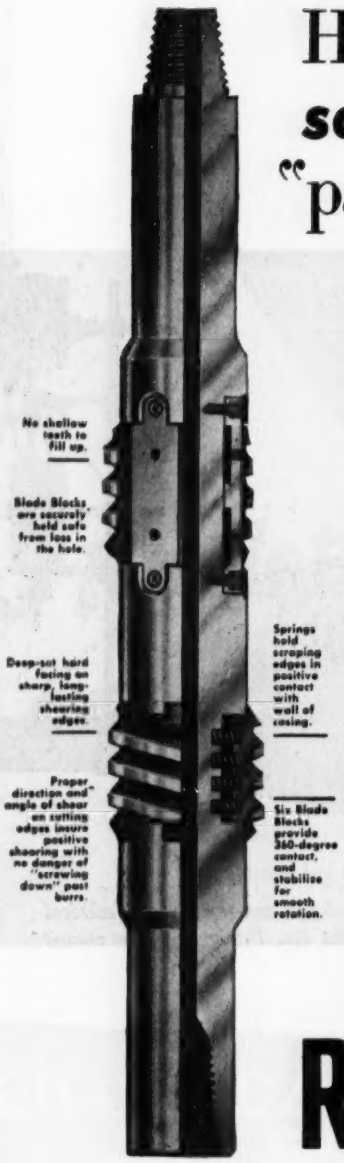
Scientific Instrument Makers

FRESHWATER ROAD, CHADWELL HEATH, ESSEX



Here's why

SCRAPING YOUR CASING "pays off"


No shallow teeth to fill up.
Blade Blocks are securely held safe from loss in the hole.
Deep-set hard facing on sharp, long-lasting shearing edges.
Proper direction and angle of shear on cutting edges insure positive shearing with no danger of "screwing down" past burrs.
Springs hold scraping edges in positive contact with wall of casing.
Six Blade Blocks provide 360-degree contact, and stabilize for smooth rotation.

Unless the inside of your casing—the vital "working surface"—is clean and smooth, there is always a possibility of trouble in future operations. Burrs from gun-shot perforations, hardened cement or mud, and even mill scale are all dangerous when the time comes to run testers or swabs, or to set retainers or packers of any description.

The Baker Model "C" ROTO-VERT Casing Scraper removes undesirable obstructions from the inside of the casing, leaving it clean and smooth. Burrs or imbedded bullets are sheared away; cement, mud and scale are scraped away, so that any down-hole work can be safely done at once, or during the years to come.

SCRAPE WHILE DRILLING OUT

The ideal time to use the ROTO-VERT Casing Scraper is during the drilling out of cement, at which time it is run as a "follow-up" behind the bit. Thus in a single run you can also remove all hardened cement, mud, burrs and scale which might later damage swabs or testers, and cause packers or retainers to set prematurely—or never set at all.

EASY TO RUN—LOW-COST RENTAL

The Baker ROTO-VERT Casing Scraper is simple to run, and will effectively clean the inside of the casing *when either rotated or reciprocated* (vertical action) The low cost is paid for many times over by freedom from future damage to bailers, swab rubbers and packers, as well as by the elimination of future delays and re-running expense.

BAKER OIL TOOLS, INC.

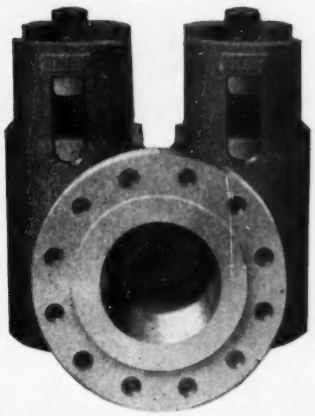
Inquiries should be directed to...

P.O. Box 2274 Terminal Annex, Los Angeles 54, California, U.S.A.

BAKER ROTOVERT CASING SCRAPER

PRODUCT NO. 620-C

FOR OIL REFINERY & CHEMICAL PLANTS



Two-hole Terminal Fitting with Flanged Side Outlet.

MILLENNIUM KEY

Millennium—Key Cast Steel Fittings

FOR STRENGTH & PRESSURE TIGHTNESS

These four bulletins give full technical information on each type of fitting we can supply. Please write for them.

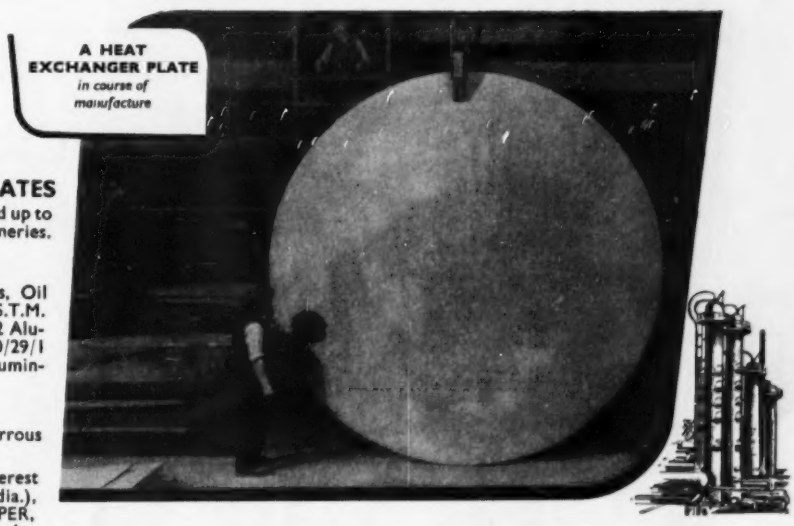
Lake & Elliot Ltd.

BRAINTREE ENGLAND

4608E

BATTERY

Tubes and Plates for Heat Exchangers



A HEAT EXCHANGER PLATE *in course of manufacture*

Birmingham Battery "True to Specification" products in non-ferrous metals are widely used in the Oil industry.

"BATTERY" CONDENSER PLATES
in Naval Brass or Yellow Metal are produced up to the heaviest sizes required by the Oil Refineries.

CONDENSER TUBES
for Heat Exchangers, Steam Condensers, Oil Coolers etc., to British Standard and A.S.T.M. Specifications in—"BATALBRA" (76/22/2 Aluminium Brass), Admiralty Mixture (70/29/1 Brass), 70/30 Brass, Cupro-Nickel and Aluminium Bronze.

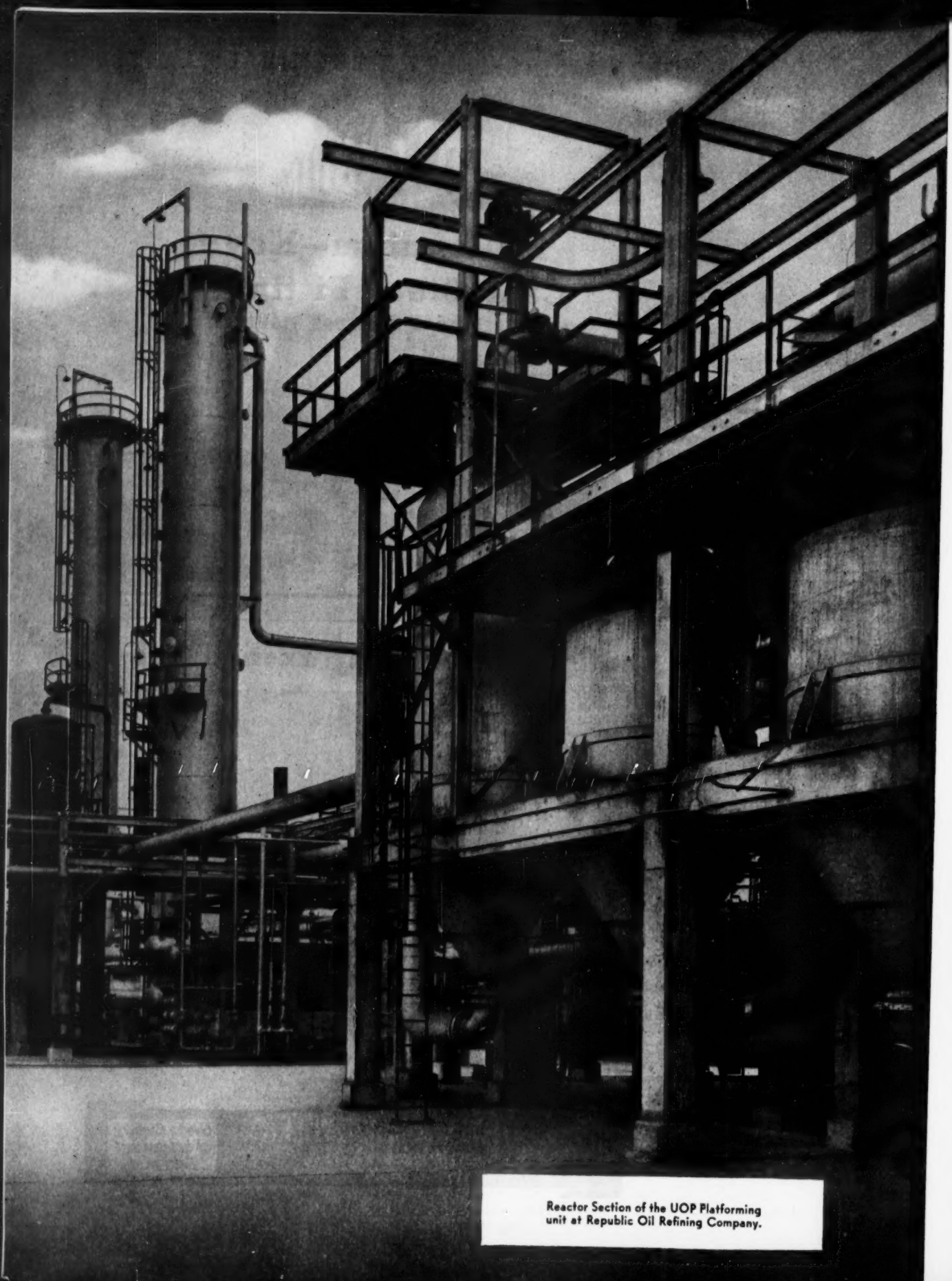
BI-METAL TUBES
for combining the properties of Non-Ferrous Tubes with Steel Tubes.

- Other "BATTERY" manufactures of interest to the Oil Industry are TUBES (up to 24" dia.), SHEETS, STRIP, ROD and WIRE in COPPER, BRASS, PHOSPHOR-BRONZE etc., to the latest British Standard Specifications. Where necessary, we should be pleased to work to customers' own requirements.

CONTRACTORS TO LEADING OIL COMPANIES

The BIRMINGHAM BATTERY and METAL CO LTD
SELLY OAK BIRMINGHAM 29

Over a Century of Independent Enterprise



Reactor Section of the UOP Platforming unit at Republic Oil Refining Company.

Platformer Helps Republic To Meet Changing Market Demands Quickly, Economically

By L. W. Robbie
Vice President and General Manager
Republic Oil Refining Co., Texas City, Texas

ADDITION of a UOP Platforming unit to our Texas City refinery has made it possible for Republic Oil Refining Company to quickly fill demands for a variety of products, thus enabling us to easily meet changing market conditions while at the same time deriving the maximum possible profit from the plant's throughput.

L. W. Robbie

The decision to add a catalytic reforming unit to our processing equipment was made only after we took a long-range look at the industry and decided that important changes in octane requirements and public demand for certain petroleum products and by-products would occur. We chose Platforming because:

(A) Careful comparison of other refiners' operating data, and Platforming's long record of commercially proved experience indicated that it was best suited to our anticipated needs.

(B) We felt the simplicity of the Platforming process would assure trouble-free operation and minimum costs.

(C) It would give us flexibility to switch from production of motor fuel to aromatics without costly revamping of equipment.

(D) In addition to increasing octane numbers, the overall quality of our finished gasoline would be improved in other ways.

Can Switch to Aromatics

Now that the Platformer has given us the flexibility that previously was lacking in our refinery operations, we are in a more favorable position to increase octane numbers quickly should the demand swing upward, or we can switch to the production of aromatics at times when market conditions justify.

The 5,500 B/SD Platformer went on stream last November 12, and it has been operating at capacity since then. Catalyst life reached 73.11 barrels of charge per pound of catalyst on the initial run. So far, we have been producing only motor fuel, with the Platformate ranging up to 89 clear octane and 98½ octane after the addition of 3 cc. TEL. The high quality of the Platformate has enabled us to meet with ease the market demands in our trade territory, which call for 87 octane regular gasoline and 95 octane premium motor fuel.

Universal Oil Products Company designed, engineered and licensed the Platformer. Construction of the unit and revamping of some existing refinery equipment was done by Procon Incorporated.

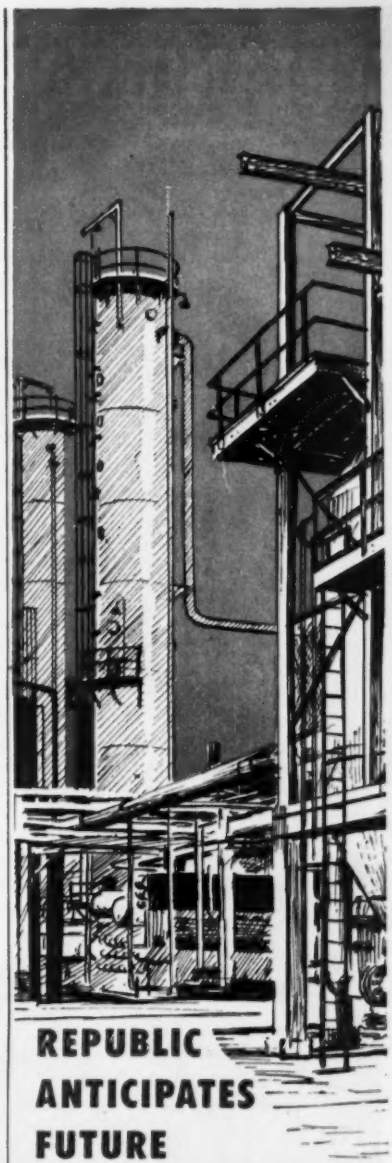
One of the unusual features of the unit is the location of an overhead cooling system for the depentanizer and rerun towers on the roof of an old pump house. The interior of the old pump house was revamped and the Platformer's control panel facilities were placed there. Only one-half of the roof area is occupied by the cooling facilities, thus leaving considerable space for the installation of other equipment should the need arise at some later date for expansion of the unit. A start in this direction was made at the time the Platformer was built by installing a fourth reactor in anticipation of the possible production of aromatics.

21,000 B/SD of Gasoline

Our Texas City refinery can turn out in excess of 21,000 barrels of gasoline per stream day through the combined output of the Platforming unit, a UOP Fluid Catalytic Cracking unit and a UOP polymerization plant. The cat cracker was operated during World War II to produce 100 octane gasoline for the Armed Forces. We conservatively estimate that 85 per cent of our total gasoline production will lead up to more than 95 octane.

Twenty different Gulf Coast sweet crudes are processed in the refinery, which has a throughput capacity of 43,000 B/SD. Charge stock to the Platforming unit boils in the range of 220 to 400° F., and it is a heavy straight run gasoline fraction prepared in a separate fractionation section.

With the installation of the Platforming unit, we have climaxed a long-range program designed to produce the highest quality products which have the broadest marketable range. Our Texas City refinery now is one of the most modern in the country, and the Platformer is playing a vital role in helping us to achieve our goal of making greater volumes of higher quality products from petroleum.



REPUBLIC ANTICIPATES FUTURE OCTANE NEEDS WITH UOP PLATFORMER

designed, engineered and licensed by

UNIVERSAL OIL PRODUCTS COMPANY

30 ALGONQUIN ROAD,
DES PLAINES, ILL., U. S. A.
Laboratories: RIVERSIDE, ILLINOIS

Universal Service Protects Your Investment

Representative: F. A. TRIM,
BUSH HOUSE, ALDWYCH,
LONDON, W.C.2

TRIANGLE Valves

FORGED STEEL GATE VALVE

FOR THE PETROLEUM AND ALLIED INDUSTRIES

FORGED STEEL

Screwed Ends. Sizes ¼" to 2". Pressures from 150 to 1500 lbs. per sq. in.

Flanged Ends. Sizes ½" ¾" 1" & 1½". Pressures 150, 300 & 600 lbs. per sq. in.

CAST STEEL

Flanged Ends. Sizes 2" to 12". Pressures 150, 300 & 600 lbs. per sq. in.

TRIANGLE VALVE CO. LTD.

Phone: 82631 (6 lines) Telegrams & Cables: TRIVALVE, WIGAN

LAMBERHEAD GREEN - WIGAN - ENGLAND

STANDARD METHODS

FOR

TESTING PETROLEUM

AND

ITS PRODUCTS

(THIRTEENTH EDITION–1953)

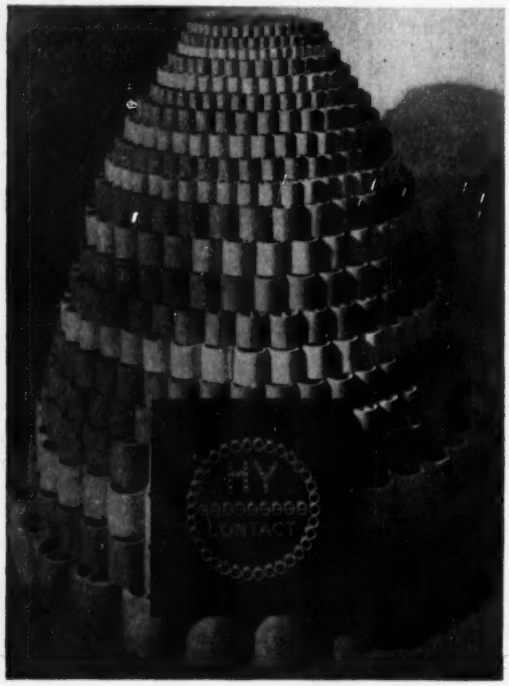
755 pages 168 Diagrams

Price 40s. post free

Obtainable from

The Institute of Petroleum

26 Portland Place, London, W.1



The Pioneers of Tower Packing

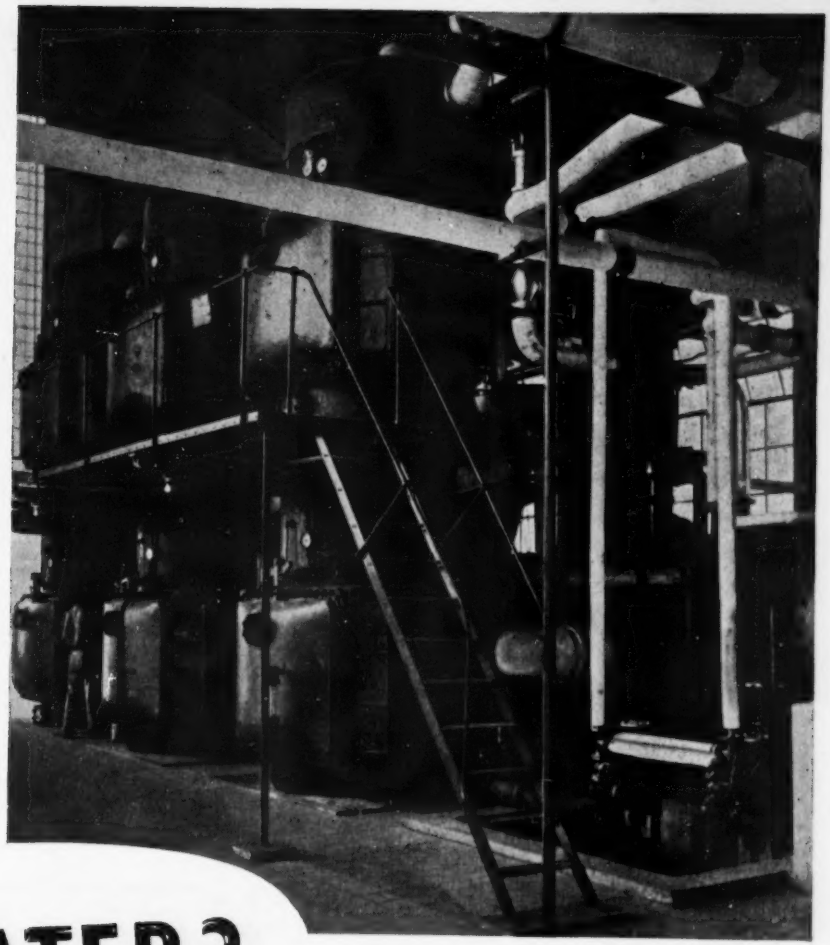
THE HYDRONYL SYNDICATE LTD.

14 GLOUCESTER RD., LONDON, S.W.7

Telephone: WEStern 4744 Telegrams: HYDRONYL · KENS · LONDON

ADVERTISERS

Babcock & Wilcox Ltd.	ii
Baird & Tatlock (London) Ltd.	vii
Baker Oil Tools Inc.	viii
Birmingham Battery & Metal Co. Ltd.	ix
Peter Brotherhood Ltd.	Sept
W. P. Butterfield Ltd.	Sept
A. F. Craig & Co. Ltd.	*Back cover*
Dorman & Smith Ltd.	xiv
Electroflo Meters Co. Ltd.	xvi
English Drilling Equipment Co. Ltd.	v
Evershed & Vignoles Ltd.	Sept
Foster Wheeler Ltd.	xv
Foxboro-Yoxall Ltd.	Sept
W. J. Fraser & Co. Ltd.	Sept
General Refractories Ltd.	iv
Matthew Hall & Co. Ltd.	i
Hayward-Tyler & Co. Ltd.	July
F. A. Hughes & Co. Ltd.	Sept
Hydronyl Syndicate Ltd., The	xii
Wm. Kenyon & Sons Ltd.	vi
Richard Klinger Ltd.	iii
Lake & Elliott Ltd.	ix
Lincoln Electric Co. Ltd.	Sept
A. & J. Main & Co. Ltd.	Sept
Metal Propellers Ltd.	Sept
Metropolitan-Vickers Electrical Co. Ltd.	Sept
L. A. Mitchell Ltd.	Sept
A. P. Newall & Co. Ltd.	Sept
Newman, Hender & Co. Ltd.	Sept
Power-Gas Corporation Ltd., The	Sept
Procon (Gt. Britain) Ltd.	Sept
Pulsometer Engineering Co. Ltd.	June
Quasi-Arc Co. Ltd.	June
Rubery, Owen & Co. Ltd.	July
South Durham Steel & Iron Co. Ltd.	Sept
Triangle Valve Co. Ltd.	xii
Universal Oil Products Co.	x & xi
G. & J. Weir Ltd.	xiii
Henry Wiggin & Co. Ltd.	*Inside back cover*
Woodfield Hoist and Associated Industries Ltd.	Sept
Yorkshire Copper Works Ltd., The	Aug



Can you drink SEA WATER?

Weir Evaporating and Distilling Plant, by providing ample supplies of fresh water distilled from sea water, has made possible the economic development of many areas with no natural supply of fresh water.

Ships too, with Weir Evaporators, can make the longest voyages without buying fresh water en route, leaving more room for paying cargo, and always being sure of pure fresh water for all the ship's services.

Write for Publication No. IH. 151

The illustration shows a sextuple effect plant which is producing 300 tons of fresh water daily from sea water.

G. & J. WEIR LTD
CATHCART GLASGOW

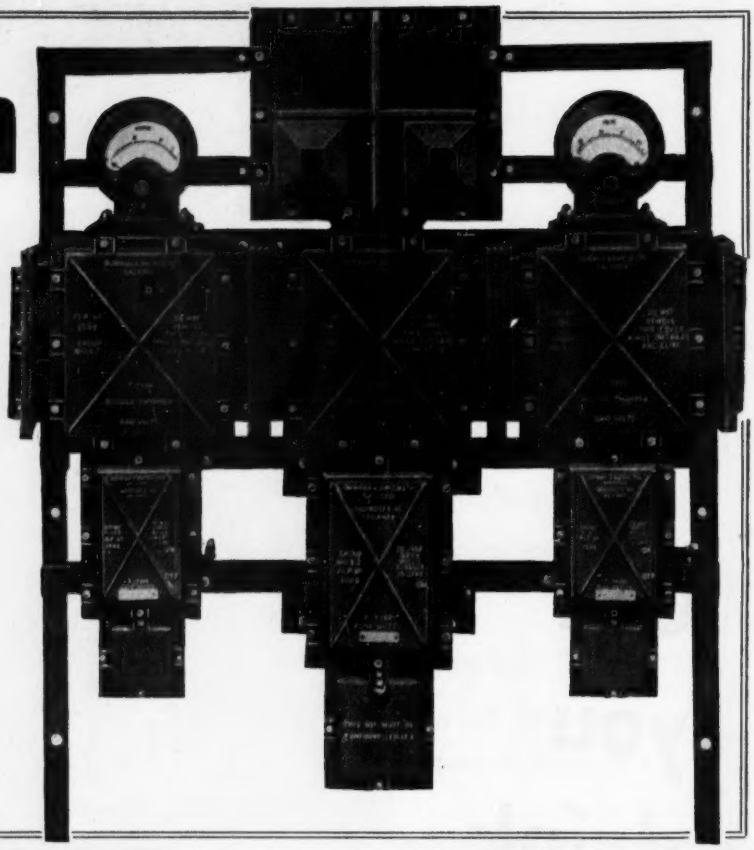
DORMAN

Buxton
Certified. . .

FLAMEPROOF
EQUIPMENT

For details
DORMAN & SMITH LTD
MANCHESTER 5

ORDSAL



The Post-War Expansion of the U.K. Petroleum Industry

Being the full report of the 1953 Summer Meeting of The Institute of Petroleum

220 pages Illustrated

Price **25s. 0d.** post free

Obtainable from

The Institute of Petroleum
26 Portland Place, London, W.1.

ASTM—IP PETROLEUM MEASUREMENT TABLES

Prepared jointly by the Institute of Petroleum and the American Society for Testing Materials, these standardized tables will be of incalculable benefit to all concerned with the measurement of petroleum products.

The Tables are available in three editions, viz:

American (U.S. units of measurement)	Price **63s.** (**$8.75**)
British (Imperial units of measurement)	Price **50s.** (**$7.00**)
Metric (Metric units of measurement)	Price **55s.** (**$7.70**)

and are obtainable from

American Society for Testing Materials,
1916 Race Street, Philadelphia, Pa., U.S.A.

Institute of Petroleum,
26 Portland Place, London, W.1

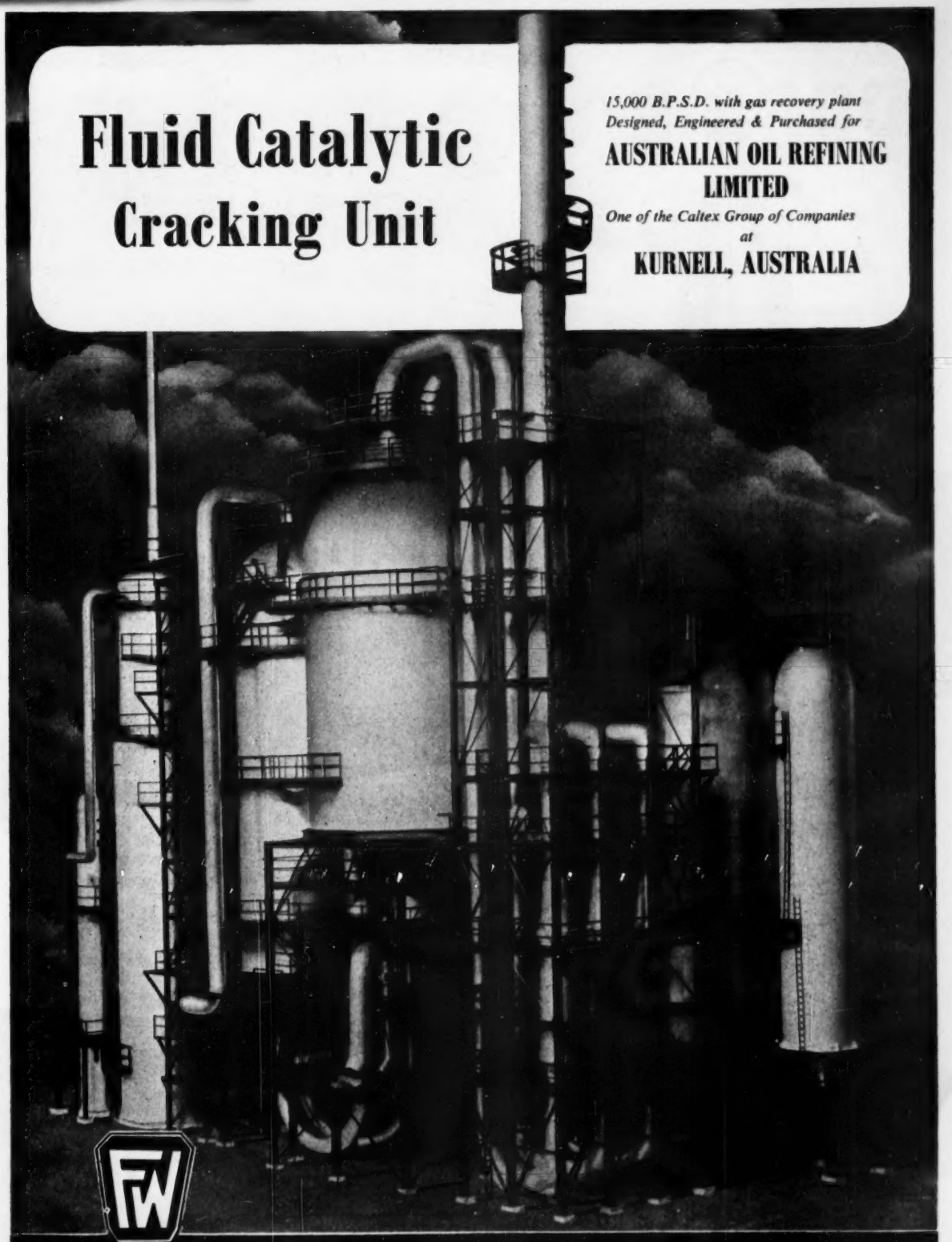
Fluid Catalytic Cracking Unit

15,000 B.P.S.D. with gas recovery plant
Designed, Engineered & Purchased for

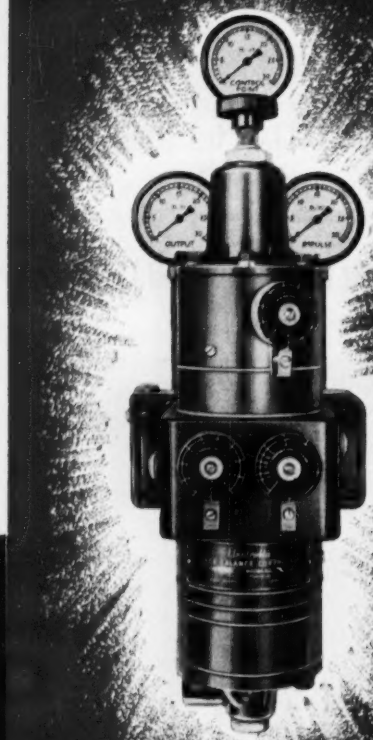
AUSTRALIAN OIL REFINING LIMITED

One of the Caltex Group of Companies
at

KURNELL, AUSTRALIA



FOSTER WHEELER *London New York and Paris*



- Continuous Force-Balance Principle
- Highest Accuracy and Response Speed
- Mechanical Motion Reduced to ·001"
- Single, Two-and Three-Term Control
- Simple to Install and Service
- Suitable for a Wide Variety of Plant: No Fire or Explosion Risk
- Local or Remote Control

FLOWS

PRESSURES

pH

TEMPERATURES

ABSOLUTE PRESSURES OR VACUA

DENSITIES

DIFFERENTIAL PRESSURES

LIQUID INTERFACE LEVELS

VAPOUR PRESSURES

LIQUID LEVELS

-all under automatic control

CONSTANTLY... ACCURATELY... RELIABLY...

ELECTROFLO SERIES 3000 Air-operated Automatic Controllers greatly simplify control of process plant however complicated or extensive. The versatility of the standardised interchangeable units affords highly efficient control in the widest variety of applications.

Send for Catalogue 90 for full details and specifications (Department **P.I.**)

ELECTROFLO Series 3000 Air-Operated AUTOMATIC CONTROLLERS

ELECTROFLO METERS COMPANY, LIMITED,
Head Office: Abbey Road, Park Royal, LONDON, N.W.10.
Telephone: ELGar 7641. Telegrams & Cables: ELFLOMETA, HARLES LONDON
Factories: Abbey Road, London, N.W.10 and at Maryport, Cumberland.

Look at it this way—

The enemies of metal — heat and corrosion — are never far from the metallurgist's mind. The many ways in which Wiggin Nickel alloys help to combat these problems are regularly described in our periodical. Copies of the current and future issues sent free of charge, on request, to all those who are interested.

CONTENTS OF THE CURRENT ISSUE INCLUDE:

Developments in Electrical Resistance alloys.

Inconel Pots for Alkali Fusions

'Masser' Resistances . . . manufacture of electrical resistance elements.

Permalloy 'C'. A Nickel-iron alloy.

Monel in ignition systems.

Pulse-jet Engine Developments.

Metal Pick-up in Pea and Tomato Processing.

All done by Springs . . . Nimonic 90 springs in the heat treatment of twist-drills.

To Henry Wiggin & Company Limited, Publications Department, Wiggin Street, Birmingham 16.

Please send me, free of charge, a copy of the latest issue of Wiggin Nickel Alloys, and add my name to your regular mailing list.

Name _____

Address _____

_____

HENRY WIGGIN & COMPANY LIMITED • WIGGIN STREET • BIRMINGHAM 16

ca/10

ATMOSPHERIC AND VACUUM DISTILLATION UNITS

COMBINED DISTILLATION, CRACKING, REFORMING AND VAPOUR PHASE TREATING UNITS

PRESSURE DISTILLATE RE-RUN UNITS

GASOLINE RECOVERY AND STABILISATION UNITS

FRACTIONATING COLUMNS AND TUBE STILLS

WAX REFINING, SWEATING AND MOULDING

A. F. Craig & Company Limited

Caledonia Engineering Works

Paisley, Scotland

London Office: 727 Salisbury House, London Wall, E.C.2. Phone: NATional 3964

C11